

**Low Cost Sorbents Screening  
&  
Engineering Analysis of Zeolite  
for Treatment of Metals Contaminated Water  
& Soil Extracts**

**Final Report**

by

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# **I INTRODUCTION**

## **Background**

Heavy metals contamination is an environmental problem at Army installations engaged in firearms training and munitions production. Weathering and corrosion of expended munitions and leaching from wastewater lagoons, landfills and burn pits, has resulted in heavy metals contamination of the soil at these facilities. Transport of metals to the groundwater has been confirmed in some locations, requiring treatment of the groundwater at the site. Certain treatment processes for contaminated soil produce metals laden extracts, which also require treatment before reuse or disposal.

The principal metals encountered in firing range soils are lead, copper and zinc. Cadmium, antimony and other metals incorporated in the munitions are sometimes found, but in lesser concentrations. Chromium is primarily associated with plating operations. Mercury is associated with various propellants and, while present in much smaller concentrations, is of concern because of its acute toxicity.

Conventional treatment technologies for groundwater and waste streams contaminated with metals include ion exchange and activated carbon. While ion exchange is generally quite effective for the removal of metals from aqueous streams, resins are expensive and must be regenerated at additional expense. Activated carbon is not as effective for most metals, and also requires regeneration. Alternative sorbents are therefore needed that are effective and economical.

## **Concept**

Low cost sorbents with a high affinity for metals that can be disposed after use may provide an economic alternative to ion exchange and activated carbon. Metals sorption capacity is reported in the literature for a variety of natural materials and industrial byproducts. This information is useful in identifying potentially useful sorbents, but is limited to the specific conditions studied. Of primary interest are those sorbents with a demonstrated affinity for the metals of interest, that are inexpensive and readily available, and that require no modification prior to use.

## **Objective**

A field ready sorption technology for treatment of metals-contaminated water and waste streams was the principal objective of this work unit.

## II LITERATURE SEARCH

An extensive literature search was conducted to identify low cost sorbents with potential for treatment of metals contaminated water and waste streams. Most sorbents requiring modification were eliminated from further consideration because of the additional cost introduced by the required chemical modifications. However, the literature indicates a very high sorption capacity for lignin, which was evaluated in a parallel study by the U.S. Environmental Protection Agency Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, Ohio. The complete text of the literature search was submitted previously.

Screening tests of the most promising sorbents identified in the literature were conducted for the primary metals of interest: Pb, Cd, Cr, Cu, Zn and Hg. The 12 sorbents tested in the screening study (marked with an asterisk) were selected from 17 sorbents considered to have potentially high sorption capacity, ready availability and low cost. The long list included:

- Bark\*
- Chitin\*
- Clay\*
- Corn cob\*
- CPEI cotton
- Crown ether\*
- Dead biomass
- Lignin\*
- Leaf mould
- Modified wool
- Moss
- Peat\*
- Sawdust
- Seaweed\*
- Xanthate\*
- Zeolite\*

Xanthate was tested in two forms: insoluble starch xanthate (ISX) and cellulose xanthate, a form of modified sawdust. Although they are expensive, crown ethers were included because of the potential for high selectivity, which could offset the high capital cost of this material for certain applications. Activated carbon (not listed) was also selected for comparison testing. As a result of the screening tests, zeolite was selected for further testing in batch, kinetic and column studies.

### III

## METHODS AND MATERIALS

### Screening Studies

#### Sorbents

Activated Carbon - The activated carbon used was granular Westates CC-601, produced from coconut shell.

Bark - Oak bark of nonspecific composition was obtained from a local sawmill. The bark was dried at 60°C for 24 hours and then ground to a near powder. The bark was not treated to prevent tannin solubilization.

Chitosan - Chitosan is produced by deacetylation of chitin, which occurs in crab shell, insects and similar organisms, and is a waste product of the crab meat canning industry. Deacetylation exposes the amine groups, which have a high affinity for metals, contained in the chitin. Chitosan practical grade (approximately 85% deacetylation of the chitin) produced from crab shell, CAS# 9012-76-4, was obtained from Sigma Chemical Company.

Corn Cob - Dry field corn was purchased locally, shelled by hand and the cobs ground in a BICO pulverizer (Model UA53). Particle size of the ground corn was variable, including flakes and sticky clumps

Crown Ether - Aldrich Chemical Company 18-crown-6, CAS# 1318-93-0, was utilized in the screening studies. Crown ethers are characterized by a ring cavity which are potentially highly selective for metals of a corresponding radii.

Clay - Two clays were utilized in the screening study: kaolinite (Albion Kaolin Company) and montmorillonite K10, CAS# 1318-93-0, Aldrich Chemical Company.

Peat Moss - Peat moss was purchased from a local nursery (Markman Peat Co).

Seaweed - Two types of seaweed were used in the screening study: *Fucus serratus* (Seaweed #1) collected from the California coast and *Ascophyllum nodosum* (Seaweed #2) purchased in the dried, pelletized form of a ratite feed supplement (Kelp Products, Inc.). The freshly collected *Fucus serratus* was dried at 65° for 24-48 hours until dry and stiff. Both types of seaweed were ground to a powder using a Brinkmann centrifugal grinding mill (Model 2716000-0).

Xanthate - Cellulose xanthate was produced in the laboratory using ground sawdust steeped in caustic soda and carbon disulfide. This procedure introduces to the sawdust a sulfur bearing group, which have been demonstrated to have a high affinity for heavy metals. The sawdust is ground to a grainy powder. Insoluble starch xanthate, CAS# 11116-64-6, was obtained from Stout's Supply in Ainsworth Iowa.

Zeolite - Zeolite was obtained from Sigma Chemical Company, CAS #1318-02-1. This is a naturally occurring zeolite, particle size  $<10\mu\text{m}$ . This zeolite contains sodium oxide, magnesium oxide, aluminum oxide and silica gel.

## **Batch Studies**

### Metal Solutions

Both single- and multi-metal solutions were used in the screening study. Single-metal solutions were used to evaluate the capacity of individual sorbents for each metal without competitive sorption effects. Multi-metal solutions were tested to more closely represent conditions encountered in actual site remediation, where a mixture of contaminants is likely to be present. A range of solution concentrations was selected that would demonstrate the performance of the sorbents at low metals concentrations and also determine the maximum capacity of the sorbents for each metal. Metal solutions were prepared using reagent grade salts (Aldrich Chemical Company):  $\text{Cd}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ ,  $\text{Cr}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ ,  $\text{Pb}(\text{NO}_3)_2$  and  $\text{HgCl}_2$ .

Single Metal Solutions - Five concentrations of single metal solution were made up for each metal. Solutions were prepared by dissolving the metal salts in distilled deionized (DDI) water. Concentrated nitric acid was added in varying amounts to dissolve the metals and the solution topped off with DDI water for a total volume of 500 ml. Solutions were buffered after sorbent addition using an acetate buffer. The buffer solution was composed of 0.63L of 0.2M acetic acid and 0.37L of 0.2M sodium acetate trihydrate. Buffer addition is more fully described under the batch study procedure. Approximate initial solution concentrations after buffering are given in Table 3.1. Selected initial chromium concentrations were lower than for the other metals because Cr sorption was expected to be less.

Table 3.1 Approximate Initial Single Metal Solution Concentrations After Buffering				
Solution	Cd (mg/L)	Cr (mg/L)	Hg (mg/L)	Pb (mg/L)
A	20,000	10,000	20,000	20,000
B	10,000	5,000	10,000	10,000
C	5,000	2,500	5,000	5,000
D	500	250	1,000	500
E	50	25	100	50

Multi Metal Solution - A solution containing all four metals (Cd, Cr, Hg, and Pb) was prepared in DDI water. Metal salts were added to DDI water to give 50, 25, 12.5, 2.5 and 0.25 meq/L of each metal before dilution with the buffer. Concentrated nitric acid was used to solubilize the metals, as for the single metal solutions. Analysis of the solutions, however, indicates that the number of equivalents dissolved in each solution were not equal for each metal. No precipitate was visible which suggests that either some metals were complexed in the mixed metal solution, or that a very fine precipitate was present, either of which might result in lower indicated concentrations of some metals. Actual concentrations for each metal are given in Table 3.2.

Table 3.2 Initial Metal Concentrations in Mixed Metal Solutions After Buffering				
Metal Solution	Cd (mg/L)	Cr (mg/L)	Hg (mg/L)	Pb (mg/L)
A	2244	721	2425	3460
B	1230	360.8	1153	1880
C	537	124.7	374	825
D	122.6	31.64	104.6	163
E	10.74	3.43	6.6	16.6

### Batch Procedures

Kinetic tests to determine the necessary contact time for equilibrium were conducted on zeolite, seaweed #2, cellulose xanthate and ISX using a 5000 mg/L solution of lead and 5g sorbent with the following contact times: 15, 30, and 45 minutes, and 1, 2, 4, 6, 10, 15, 20, 25 and 30 hours. Results of the kinetic testing indicated that 30 hours constituted a sufficient contact time for these sorbents, and it was assumed to be adequate for all the sorbents to be tested. Actual contact time varied from 30 to 37 hours. Batch and kinetic studies were conducted using the following general procedure:

- 5.0 g sorbent ( $\pm 0.01$ g) was weighed into a 125-ml Nalgene bottle
- 75 ml metal solution was added
- pH was measured using a Beckman  $\phi 45$  pH meter and adjusted to between 3 and 5, using concentrated nitric acid or 2M sodium hydroxide
- Buffer solution was added to give a solution volume of 100 ml
- pH was again measured and recorded as initial pH
- Samples were tightly capped and tumbled for the specified contact time. One blank solution sample was also tumbled as a control.
- After tumbling, pH was measured and recorded as final pH
- Samples were immediately filtered in vacuum filter apparatus using Millipore Type HA 0.45 micron filter paper.
- Filtered samples were placed in clean Nalgene bottles and stored at 4°C until analyzed for dissolved metals.

### Analysis

Elemental analysis of the filtrates was conducted using a Perkin Elmer 5100 model flame atomic absorption spectrophotometer (AA) with single element hollow cathode lamps. Cadmium, chromium and lead were analyzed according to EPA standard methods 7130, 7190 and 7420 respectively. Mercury was analyzed in the same manner according to a procedure outlined in the Perkin-Elmer handbook.

## Zeolite

### Characterization

#### Source

The zeolite used in the batch and column studies was provided to WES by the USGS. The zeolite was obtained from a natural deposit of clinoptilolite rich rock located in South Dakota (Rocky Ford SDH). Large blocks of the material were crushed and sieved into three particle size ranges: 0.5-1.0 mm, 1.0-4.0 mm, and 2.0-4.7 mm. According to X-ray diffraction analysis performed on this material (Desborough, 1996), the dilutant minerals in the zeolite, listed in order of abundance, are plagioclase, calcite, quartz, opal, K-feldspar and trace clay. The chemical composition is given in Table 3.3. The weight percent water capacity of this zeolite is 58. The material demonstrates high structural stability in acidic solutions.

Table 3.3 Chemical Composition of Clinoptilolite Rich Rock Used in Batch and Column Studies			
Component	Contribution	Component	Contribution
K	4% by weight	Zr	170 ppm
Ca	1.7% by weight	Y	20 ppm
Fe	1.4% by weight	Nb	10 ppm
Cu	20 ppm	Ce	65 ppm
Zn	60 ppm	Nd	25 ppm
Rb	90 ppm	La	30 ppm
Sr	455 ppm	Ba	700 ppm
Pb	35 ppm		

#### Cation Exchange Capacity (CEC)

The selectivity of zeolites for ammonium ions ( $\text{NH}_4^+$ ) over sodium ions ( $\text{Na}^+$ ) is used in the determination of CEC (Rhodes, 1982; Ming and Dixon, 1987). The exchange sites of the zeolite are first saturated with  $\text{Na}^+$ . Total cation exchange capacity (TCEC) is determined using a solution of  $\text{NH}_4\text{OAc}$ , which replaces the  $\text{Na}^+$  in both internal and external exchange sites.



Zeolite typically contains other exchangeable cations that could affect the determination of CEC because some zeolites may be more selective for these cations than for  $\text{Na}^+$ . The calculated CEC was therefore adjusted for the concentrations of  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$  released from the zeolite to the ammonium solutions during loading. The procedure was as follows:

- 4.0 g air dried zeolite samples were weighed out in triplicate for all three particle size ranges. Actual weight was recorded.
- The zeolite samples were placed in 40 mL centrifuge tubes
- A buffered solution of 1N NaOAc was prepared
- Sample tubes were filled with the NaOAc solution and tumbled overnight.
- Sample tubes were removed from the tumbler and placed in an ultrasonic bath for 15 minutes to disperse the particles.
- Samples were then centrifuged 15 to 30 minutes at 2000-3000 RPM until the supernatant was clear.
- Samples were then decanted and washed with NaOAc solution three more times, tumbling for 30 minutes and centrifuging as before.
- The supernatant for all four washes was combined for each sample.
- Excess interstitial  $\text{Na}^+$  was washed from the samples, once with distilled deionized (DDI) water and three times with 95% ethanol. Ethanol was selected for its small molecule size which can readily enter the internal zeolite pore spaces. Samples were centrifuged if necessary to minimize loss of zeolite during decanting. The supernatant from these washings was combined with the supernatant from the NaOAc washing.
- The total volume of the collected supernatant was measured in a graduated cylinder. Samples were collected for analysis of  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$ .
- A solution of 1.0N  $\text{NH}_4\text{OAc}$  was prepared
- $\text{NH}_4\text{OAc}$  solution was then added to the sample tubes. Samples were tumbled overnight.
- After tumbling, the sample tubes were placed in an ultrasonic bath for 15 minutes to disperse the particles.

- Samples were then centrifuged 15 to 30 minutes at 2000-3000 RPM, until the supernatant was clear. The supernatant was decanted and collected for each sample.
- Samples were washed three more times with the  $\text{NH}_4\text{OAc}$  solution. For each wash, the samples were tumbled for 30 minutes, then centrifuged. The supernatant for all four washes was combined for each sample.
- Excess interstitial  $\text{Na}^+$  was washed from the samples, once with DDI water and three times with 95% ethanol. Samples were centrifuged if necessary to minimize loss of zeolite during decanting. Supernatant was collected and combined with the  $\text{NH}_4\text{OAc}$  supernatant.
- The combined  $\text{NH}_4\text{OAc}$  and ethanol supernatant was decanted into a graduated cylinder to determine the total volume.

Total CEC was calculated as follows:

$$TCEC = \frac{C * V}{22.98 * M} * 100$$

Where:

TCEC	= Total Cation Exchange Capacity, (meq/100g)
C	= sum of $\text{Na}^+$ , $\text{Ca}^{2+}$ , $\text{Mg}^{2+}$ and $\text{K}^+$ concentrations in combined supernatant from $\text{NH}_4\text{OAc}$ washings, (mg/L)
V	= volume of combined supernatant, L
M	= mass of zeolite, g
22.98	= Equivalent weight of Na, mg/meq

### Surface Area

Specific surface area for all three particle size ranges was measured using a Gemini 2360 Surface Area Analyzer using  $\text{N}_2$  gas as the standard adsorbate. Specific surface area is calculated using a Brunauer, Emet and Teller (BET) multipoint procedure. The BET relationship is given as:

$$\frac{P}{V_a (P_o - P)} = \frac{1}{V_m C} + \frac{C-1}{V_m C} * \frac{P}{P_o}$$

where:

- P = partial pressure of the adsorbate gas, N<sub>2</sub> (atm)
- P<sub>o</sub> = saturation vapor pressure of the gas, (atm)
- V<sub>a</sub> = total volume of gas adsorbed, (mL)
- V<sub>m</sub> = volume of gas adsorbed when the entire adsorbent surface is covered with a complete unimolecular layer, (mL)
- C = constant

A plot of P/(V<sub>a</sub>(P<sub>o</sub>-P)) vs P/P<sub>o</sub> should be linear, with slope (C-1)/(V<sub>m</sub>C) and intercept 1/(V<sub>m</sub>C). From the V<sub>m</sub> so determined, the surface area relationship is given as:

$$S_{BET} = V_m a_m N * 10^{-20}$$

where:

- S<sub>BET</sub> = specific surface area, (m<sup>2</sup>/g)
- a<sub>m</sub> = molecular cross sectional area of one molecule of adsorbate gas, Å<sup>2</sup>  
(16.3Å<sup>2</sup> for nitrogen)
- N = 6.0x10<sup>23</sup>

## Batch Studies

Seven batch studies were conducted: four equilibrium tests, two kinetic tests and one selectivity test (Table 3.4).

## pH Control

Control of pH in sorption studies is particularly important to rule out the possibility of metals removal from solution by precipitation. This is typically addressed by the use of a buffer, made up of an acid with pK<sub>a</sub> (dissociation constant) near the desired pH, combined with the

conjugate base. In the screening studies, acetic acid and sodium acetate were used to maintain the pH near 4.5. Because zeolite has a high affinity for  $\text{Na}^{1+}$ , however, use of sodium acetate introduces competing ions into the metal solution. An alternative is to make up the buffer with acetic acid and a strong base, such as NaOH. This introduces much less sodium into the solution; in this case approximately 3% of the estimated zeolite capacity.

For zeolite, a third alternative exists for pH control. Zeolite releases carbonates when in contact with solution, which are responsible for the rise in pH over time. Acid washing removes most of the carbonates and provides a uniform material for study. Changes in pH are generally much smaller for acid washed zeolite than for the "unwashed" material. Batch studies were conducted using acid washed zeolite (AW) and unwashed zeolite (UW). The procedures were as follows:

#### Acid Wash -

- Prepare a 1M acetic acid/sodium acetate buffer solution
- Place 200g of raw zeolite in a beaker with 500ml buffer solution
- Leave for 24 hours, stirring occasionally
- Decant and add fresh buffer. Allow to sit for another 24 hours, stirring occasionally.
- Decant the buffer
- Rinse the zeolite three times with DDI water, or until rinse water is clear
- Dry overnight at 105°C. Cool in desiccator and weigh. Return to oven and repeat procedure in one hour. Less than 1% weight change is taken as indication of dry material.

Table 3.4 Batch Studies Conducted

Test		Conditions					
Number	Type	AW/UW	Particle Size (mm)	Sorbent Mass (g)	Solution	Approx. Initial Conc $C_0$ (mg/l)	Contact Time
1	Equil.	UW	0.5-1 1.0-4.0 2.0-4.7	1,5,7,5,15	Synthetic	Pb: 30K	2 hrs
2	Equil.	AW&UW	0.5-1 1.0-4.0 2.0-4.7	1,5,7,5,15	Synthetic	Pb: 20K	2 hrs
3	Equil.	AW	2.0-4.7	1,5,7,5,15	Picatinney	Pb: 13 Zn: 45 Cu: 44	2 hrs
4	Kinetic	AW	2.0-4.7	5	Picatinney	Pb: 13 Zn: 45 Cu: 44	0.25 - 30 hrs
5	Kinetic	UW	0.5-1.0 1.0-4.0 2.0-4.7	5	Synthetic	Pb: 1K Zn: 50 Cu: 50	0.25 - 30 hrs
6	Selectivity	AW	2.0-4.7	5	Synthetic	A: Pb: 500 Ca: 100 B: Pb: 50 Ca: 100	2hrs & 24 hrs
7	Equilib	AW	0-4.7	1,5,7,5,15	FBH Soil Extract	Pb: 500 Zn: 2 Cu: 7	24 hrs

#### DDI Wash -

- Rinse zeolite with DDI water until all fine material is removed and water is clear.
- Dry overnight at 105°C or until dry, as described above.

#### Kinetic Studies

Kinetic studies were conducted on unwashed zeolite, using separate solutions of Pb, Cu and Zn. The unwashed zeolite was used to determine how rapidly a pH increase occurred in the solution and to evaluate how much of the removal demonstrated by unwashed zeolite was attributable to sorption and how much to precipitation. The kinetic study was also conducted to determine the contact time necessary to achieve equilibrium. The procedure was as follows:

- 5.0 g unwashed zeolite was weighed into each of 10, 250 mL, Nalgene bottles .
- Three solutions were prepared using metal salts and DDI water, as indicated in Table 3.5.

Table 3.5 Metals Solutions for Kinetic Studies	
Salt	Concentration mg/L
Pb(NO <sub>3</sub> ) <sub>2</sub>	1000
CuSO <sub>4</sub> ·5H <sub>2</sub> O	50
Zn(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	50

- Add 100 mL of solution to each bottle
- Immediately read and record the pH of each sample. Record as initial pH.
- Cap all bottles tightly
- Tumble at speed setting 5.5, removing one bottle at each of the following times for analysis: .25, .5, 1, 2, 4, 10, 15, 20, 24, 30 hrs
- Immediately after removing each sample from the tumbler, measure pH and record as final pH,

- Centrifuge samples as soon as possible after removing from tumbler, at 12,000 rpm for 5 minutes. Repeat if liquid/solid separation has not occurred.
- After centrifuging, decant liquid into 125 mL Nalgene bottles.
- Dry solids in oven at 105°C for 24 hrs. Cool in desiccator and weigh. Return to oven for one hour. Cool and reweigh. Repeat if necessary until weight change is no more than 1%.
- Place dried samples in 30 mL Nalgene bottles
- Store liquid and solid samples in environmental chamber at 4°C until analyzed on AA.

#### Picatinney Arsenal Extract -

An additional kinetic study was conducted using 2-4.7 mm acid washed zeolite with extract from a metals and organics contaminated soil from Picatinney Arsenal. The pH of this solution is very low, approximately 1.1 to 1.2. The extract was prepared by sequential surfactant extraction of organics contamination followed by acid extraction of metals from soil taken from a burn pit. A number of metals and organics compounds were present in the soil. Analysis of the extract for Pb, Zn and Cu indicated the following composition (Table 3.6):

Table 3.6 Measured pH and Pb, Cu and Zn Concentrations in Picatinney Extract	
Metal	Concentration (mg/l)
Lead	12.8
Zinc	45.48
Copper	40.29
PH	1.29

#### Equilibrium Batch Tests

Equilibrium batch studies were conducted on both acid washed and unwashed zeolite, using a single solution concentration of Pb for varying sorbent weights. Use of a single solution concentration has the advantage of maintaining uniform solution activity. The procedure was as follows:

- 5.0 g of zeolite was weighed into a 250 mL Nalgene bottle for 0.5-1.0, 1.0-4.0 and 2.0-4.7 mm particle sizes.
- Prepare synthetic solutions using  $\text{Pb}(\text{NO}_3)_2$
- Add 100 mL to each sorbent sample
- Immediately read the pH and record as initial pH
- Cap bottles tightly
- Tumble at speed setting 5.5 for specified contact time
- Remove from tumbler. Immediately measure pH and record as final pH
- Centrifuge for 5 minutes at 12,000 rpm. Repeat if solid and liquid phases have not separated.
- Decant liquid into 125mL Nalgene bottle. Store in environmental chamber at 4°C until analyzed for Pb concentration on AA
- Dry solids in drying tins at 105°C for 24 hrs. Cool in desiccator and weigh. Return to oven for one hour. Cool and reweigh. Repeat procedure until weight change is less than 1%.
- Place solids in 30mL Nalgene bottles and store in environmental chamber at 4°C until digested and analyzed for Pb on AA

#### Picatinney Arsenal Extract -

An additional batch study was conducted with the extract from an organics and metals contaminated soil from Picatinney Arsenal using 2.0-4.7mm acid washed zeolite, at 1, 5, 7.5 and 15 g. Extract preparation was previously described under the kinetic study procedures. Contact time was 2 hours. A second study was conducted with contact time of 24 hours.

#### Selectivity Tests

A selectivity test was performed using acid washed zeolite and two solutions. The procedure was as for the equilibrium batch tests, with the following differences:



- A 1L solution was prepared using  $\text{Pb}(\text{NO}_3)_2$  and  $\text{Ca}(\text{NO}_3)_2$  in DDI water. Solution A contained 500 mg/l Pb and 100 mg/l Ca. Solution B contained 50 mg/l Pb and 100 mg/l Ca.

- Samples were tumbled for 2 hrs and 24 hrs.

## Column Studies

Ten column studies were conducted (Table 3.7). Because surface area was relatively consistent for all three particle size ranges evaluated, the largest particle size (2.0-4.7 mm) was selected for nine of the studies because it was expected to have the best hydraulic properties. The last study utilized the smallest particle size range (0.5-1.0 mm) for performance comparison. Both acid washed and unwashed zeolite were tested in the columns.

Three flow rates below  $40.7 \text{ l/min}\cdot\text{m}^2$  (1 gal/min·ft<sup>2</sup>) were selected to minimize side wall effects and demonstrate the relationship between capacity and flow rate. In terms of bed volumes, the flow rates were 3 BV/hr (60 ml/min), 1 BV/hr (20 ml/min) and 0.3 BV/hr (6.0 ml/min). Column tests were conducted in custom made plexiglass columns (Figure 3.1). Inside diameter was 5.08 cm (2 inches). Bed length was 60.96 cm (24 inches). One hundred micron stainless steel porous plates were used at either end of the column bed to minimize particulate transport and distribute flow. Influent and effluent tubing was Tygon. Valves and fittings in contact with the extract were stainless steel. Extract was delivered to the columns with Masterflex digital peristaltic pumps.

Table 3.7. Column Studies Conducted with South Dakota Zeolite				
Column Number	Packing Material	Particle Size (mm)	Flow Rate	Duration
1	Empty - Control	N/A		12 hrs
2	Unwashed zeolite (UW)	2.0-4.7	3 BV/hr	12 hrs
3	Acid Washed zeolite (AW)	2.0-4.7	3 BV/hr	12 hrs
4	UW	2.0-4.7	1 BV/hr	12 hrs
5	AW	2.0-4.7	1 BV/hr (stop flow)	14 hrs
6	UW	2.0-4.7	0.3 BV/hr	12 hrs
7	AW	2.0-4.7	0.3 BV/hr	12 hrs
8	AW	2.0-4.7	1 BV/hr	15 hrs
9	UW	2.0-4.7	0.3 BV/hr	7 days
10	UW	0.5-1.0	0.3 BV/hr	12 hrs

### Extract Preparation

Columns were challenged with an acidic waste stream produced in the lab from extraction of a metals contaminated soil obtained from Fort Benjamin Harrison (FBH). The extract was prepared as follows:

- A 0.01M CaO solution was prepared
- Approximately 15 kg metals contaminated soil (at in-situ water content) was placed in a 100L (30 gal) Nalgene tank. The soil was slurried with the CaO solution at approximately 15% solids content to oxidize. The slurry was mixed with a Lightning mixer for a period of 5 hours, and then allowed to settle until the supernatant was clear (12-24 hours).
- After settling, the CaO supernatant solution was pumped off and discarded.
- A 0.1M solution of Acetic Acid was prepared from concentrated glacial acetic acid with normality ~17.6. The acetic acid solution was added to the wet soil, to give approximately 15% solids content. This was mixed for a period of 5 hrs, then allowed to settle.
- The acetic acid extract was filtered in a pressure filter using Whatman 5, 2.5  $\mu$ m filter paper. The filtered extract from subsequent extractions was combined in three 208.3 l (55 gallon) barrels.
- Samples were taken from each of the extract barrels and analyzed on the AA for a minimum lead concentration of 200 mg/l. The extract was also analyzed for Ca, Cu, Cd, Cr and Zn. pH was measured with a Beckman  $\phi$ 45 pH meter.

### Column Packing

Columns were loose packed with zero head space using oven dried zeolite at zero head space. The columns were tapped during loading to consolidate the material. The weight of zeolite loaded to the columns was recorded. Bulk density of the material packed in the columns was calculated as the mass divided by the packed bed volume. For 5.08 cm (2 inch) diameter columns with 60.96 cm (2 feet) bed length and no head space this is given as:

$$\rho_b = \text{mass(g)}/1235.6(\text{cm}^3)$$

### Run and Sampling Procedures

After loading, the columns were flushed with DDI water until the effluent ran clear and the zeolite appeared to be fully saturated (approximately 5-15 minutes). The influent tubing was purged of DDI water with extract up to a three way valve at the bottom of the column. The first

influent sample was then taken from the valve, and flow was then directed through the DDI saturated column. This was taken to be time zero.

Influent was sampled manually at the three way valve at three hour intervals throughout the duration of flow. Effluent samples were taken automatically using an ISCO Model 3700 portable sampler. Effluent was allowed to flow into a collection reservoir, which was emptied by the sampler at five to ten minute intervals, depending upon the rate of flow. The sampler was set to advance to a new sample bottle after each sampling event. Sample concentrations therefore represent a composite of the five or ten minute interval over which they were collected. For the periods that the columns were running, this was considered reasonably comparable to discrete sample points.

At the end of the run time, flow was shut off. The column was drained and the loaded zeolite transferred in 5.08 cm (2 inch) increments to 125 ml Nalgene sample bottles. Effluent samples were transferred to 125-250 ml Nalgene sample bottles. Excess effluent was combined for disposal. All samples were stored in an environmental chamber at 4°C for pH and metals analysis.

### Analysis

Elemental analysis was conducted using a Perkin Elmer 5100 model flame atomic absorption spectrophotometer (AA) with single element hollow cathode lamps. Liquid samples were filtered and analyzed for dissolved metals. Solid samples were digested using Method 3051: Microwave Assisted Acid Digestion of Sediments, Sludges, Soils and Oils. Lead, copper, cadmium, chromium, zinc and calcium were analyzed according to EPA standard methods 7420, 7210, 7130, 7190, 7950 and 6010 respectively.

## IV RESULTS

### Screening Studies

For all batch tests, sorption from solution was calculated using the following equation:

$$q_e = \frac{(C_{initial} - C_{final}) \times V}{M_{sorbent}}$$

where $q_e$	= adsorption, mg/g
$C_{initial}$	= initial metal concentration, mg/L
$C_{final}$	= final metal concentration, mg/L
$V$	= solution volume, L (0.1 L)
$M_{sorbent}$	= mass of sorbent in sample, g

### Kinetic Tests

The kinetic tests indicated that zeolite, seaweed #2 and ISX reached equilibrium within the first 15 minutes of contact. Although shorter contact times were not evaluated, the sorption kinetics may be even more rapid than this. For cellulose xanthate, Pb sorption peaked at approximately 1 hour, then declined to an apparent equilibrium at 15 hours. This suggests that optimum contact time may differ from equilibrium, and will be unique for each sorbent. The kinetic tests do indicate that the 30 hour contact time used in the batch studies is sufficient to establish equilibrium for Pb sorption for the sorbents tested.

### Single Metal Batch Tests

Isotherms were prepared for each sorbent and each metal (Figures 4.1 through 4.4). As indicated by the isotherms, zeolite was the most effective sorbent for Cd, Cr and Pb. Even at the highest initial solution concentration, 100% sorption of lead from solution was achieved with zeolite. Seaweed #2 had the second highest sorptive capacity for Cd and Cr. ISX had the second highest capacity for lead, followed closely by seaweed #2. Zeolite was almost completely ineffective for Hg, which sorbed more readily to carbon and other organic sorbents.

Montmorillonite and kaolinite were relatively ineffective compared to the other sorbents. Corn cob performed poorly in all cases.

Although an effective sorbent, filtration was slow for seaweed #2. Some modification would be necessary to make continuous flow treatment using seaweed #2 feasible. Also, bark and cellulose xanthate leached a considerable amount of color into solution. Crown ether was soluble in the metal solutions and chitosan and seaweed #1 became emulsified. Attempts to break the emulsions using filtration, centrifugation, pH adjustment, heating and freeze/thaw treatment were unsuccessful. No sorption data was therefore obtained for the crown ether, chitosan or seaweed #1. Maximum capacities for each metal for the other sorbents are given in Table 4.1.

Table 4.1 Maximum Sorbent Capacities for Single Metal Solutions				
Sorbent	Pb (mg/g)	Cr (mg/g)	Cd (mg/g)	Hg (mg/g)
Zeolite	368.2	80.5	194.2	2.6
Seaweed #2	241.8	59.2	105.8	177.3
ISX	270.9	47.6	99.8	99.4
C. Xanthate	210.5	22.6	105.9	257.0
Peat Moss	111.9	35.2	74.4	95.9
Bark	67.6	7.4	22.4	127.4
Montmorillonite	48.0	15.4	51.2	2.6
Kaolinite	25.4	20.0	0.20	0.07
Corn Cob	18.4	7.6	2.4	22.3
Activated Carbon	142.8	10.7	28.4	277.3

### Multi Metal Batch Test

The multi-metal batch test was performed to provide an indication of the selectivity sequence for Cd, Cr, Pb and Hg for each sorbent. Isotherms for each sorbent are plotted in Figures 4.5-4.14. Some sorbents display fairly distinct selectivity sequences. Zeolite is particularly notable, demonstrating extremely high adsorption for Cr, Cd and Pb but little Hg sorption. Results are mixed for some of the sorbents, such as corn cob, where selectivity

appears to be a function of initial concentration. This is also illustrated for Cd and Cr for cellulose xanthate, ISX and seaweed #2, where selectivity is highest for Cd except at the highest concentration test, at which more Cr was sorbed. However, because the increased Cr removal is relatively abrupt, this is thought to be the result of precipitation rather than competitive sorption. Precipitates could form as hydroxides or as metal acetates. A qualitative selectivity sequence for the sorbents tested is given in Table 4.2.

Table 4.2 Qualitative Selectivity Sequence - Multi-metal Testing	
Sorbent	Selectivity Sequence
Bark	Pb=Hg>Cr>Cd
Carbon	Hg>Pb=Cr>Cd
Corn cob	Pb=Hg>Cr=Cd
Cellulose xanthate	Hg>Pb>Cd>Cr
ISX	Hg>Pb>>Cd>Cr
Kaolinite	no clear sequence
Montmorillonite	Cr>>Pb=Cd>Hg
Peat moss	Cf=Pb>Hg=Cd
Seaweed #2	Pb>Hg>Cd>Cr
Zeolite	Pb>Cd>Cr>>Hg

## Curve Fitting

The data was fitted to the Freundlich and Langmuir isotherms. The Langmuir isotherm is given as (Faust and Aly 1987):

$$q_e = \frac{x_m KC}{1 + KC}$$

where  $q_e$  = mass of solute sorbed per unit mass of sorbent, mg/g  
 $C$  = equilibrium concentration of solute in solution, mg/L  
 $x_m, K$  = constants

The Langmuir model assumes single-layer adsorption in which the layer is one molecule thick and each of the adsorption sites have equal affinities for solute metals. The constant  $x_m$  corresponds to the mass of solute per unit weight of sorbent required to form a complete monolayer.  $K$  is associated with the energy of adsorption.

The Freundlich equation is given as (Faust and Aly 1987):

$$q_e = KC^{\frac{1}{n}}$$

where  $q_e$  = mass of solute sorbed per unit mass of sorbent, mg/g  
 $C$  = equilibrium concentration of solute in solution, mg/L  
 $n, K$  = constants.

The Freundlich model assumes that the sorbent surface consists of different types of adsorption sites with unequal affinities for solute molecules. The terms  $K$  and  $1/n$  are associated with adsorption capacity and adsorption intensity, respectively. The larger  $K$ , the higher the sorbent capacity and the smaller the value of  $1/n$ , the stronger the adsorption bond. The Langmuir equation incorporates a maximum capacity term  $x_m$  and can be applied at saturation. The Freundlich equation does not, and is not applicable at saturation. Good data fit to the Freundlich or Langmuir does not necessarily confirm the assumptions of the models. Typically, the Freundlich equation provides a better fit to data than the Langmuir, and generally applies better to mixed solutes and dilute solutions.

A fit of the isotherms is commonly obtained by linear regression of the linearized forms of the equations:

Langmuir: 
$$\frac{1}{q_e} = \frac{1}{x_m} + \frac{1}{Kx_m} \frac{1}{C}$$

Freundlich: 
$$\log q_e = \log K + \frac{1}{n} \log C$$

Application of linear regression resulted in negative values for some of the data. Therefore, nonlinear regression was used to determine the Langmuir and Freundlich constants, which are given in Tables 4.3 - 4.6. The Langmuir constant ( $x_m$ ) values obtained in the batch testing indicate that seaweed #2 had the greatest capacity overall for the metals tested, superior even to Zeolite for Cd and Cr. Lead sorption data for Zeolite, which appeared from the batch isotherms to have the highest sorption capacity for lead, could not be compared because the data could not be fit to a model for that solute.



Table 4.3 Sorption Parameters for Cadmium Uptake						
Model	Freundlich			Langmuir		
Sorbent	K	n	R <sup>2</sup>	K	$K x_m$	R <sup>2</sup>
Bark	1.52	3.34	0.6825	6.32e-04	229.6	0.7729
Carbon	0.908	2.82	0.9803	4.21e-04	330.8	0.9886
Corn Cob	0.429	4.65	0.7474	1.01e-02	22.53	0.9839
Cellulose Xanthate	1.83	2.37	0.9942	1.95e-04	1140	0.9876
ISX	39.0	20.0	0.6081	6.01e-01	667.8	0.8203
Kaolinite	Data could not be fit to equations					
Montmorillonite	9.90e-03	1.12	0.9856	1.02e-05	4403	0.9848
Peat Moss	3.36	3.00	0.9677	3.57e-04	994.5	0.9690
Seaweed #2	28.59	3.40	0.7218	1.18e-03	4464	0.8629
Zeolite	25.66	4.26	0.9187	4.98e-03	1199	0.9977

Table 4.4 Sorption Parameters for Chromium Uptake							
Model	Freundlich			Langmuir			
Sorbent	K	n	R <sup>2</sup>	K	X <sub>m</sub>	R <sup>2</sup>	
Bark	1.09	4.39	0.8524	2.21e-02	26.82	0.9408	
Carbon	3.21	17.5	0.0738	2.82e+00	35.68	0.2559	
Corn Cob	2.98e-03	1.15	0.9440	6.79e-03	22.31	0.0520	
Cellulose Xanthate	1.90	3.50	0.8862	3.58e-03	122.9	0.9926	
ISX	2.83	10.1	0.0483	7.28e-03	68.02	0.1910	
Kaolinite	0.0137	1.25	1.0000	1.28e-04	37.3	0.9999	
Montmorillonite	1.24	3.70	0.9697	3.93e-04	419.2	0.8694	
Peat Moss	0.301	1.90	0.9680	1.82e-04	938.3	0.9517	
Seaweed #2	6.82	2.33	0.8819	1.20e-03	4304	0.9053	
Zeolite	22.1	7.34	0.9180	6.41e-02	164.0	0.8667	

Table 4.5 Sorption Parameters for Lead Uptake							
Model	Freundlich			Langmuir			
Sorbent	K	n	R <sup>2</sup>	K	$\frac{K X_m}{n}$	R <sup>2</sup>	
Bark	6.49	3.69	0.9729	1.17e-03	883.7	0.9811	
Carbon	4.44	2.75	0.9836	3.79e-04	3161	0.9480	
Corn Cob	2.27e+00	4.91	0.6933	3.90e-03	215.8	0.9051	
Cellulose Xanthate	14.6	3.72	0.9725	1.76e-03	1166	0.9280	
ISX	67.1	5.92	0.8867	3.41e-02	6277	0.9806	
Kaolinite	0.0136	1.54	0.9841	4.76e-05	17.4	0.9667	
Montmorillonite	1.09	2.53	0.9939	2.72e-04	458.8	0.9893	
Peat Moss	18.3	5.04	0.9729	2.11e-03	9116	0.9940	
Seaweed #2	80.7	3.16	0.9615	3.93e-03	41171	0.9652	
Zeolite	Data could not be fit to equations						

**Table 4.6 Sorption Parameters for Mercury Uptake**

Model	Freundlich			Langmuir		
	K	n	R <sup>2</sup>	K	$K \times \frac{x_m}{n}$	R <sup>2</sup>
Sorbent						
Bark	0.958	1.89	0.9908	1.81e-04	8.194	0.9861
Carbon	8.73	1.94	0.9875	3.13e-03	3.384	0.9961
Corn Cob	4.00e-01	2.20	0.9917	4.39e-04	2.28.9	0.9488
Cellulose Xanthate	0.398	1.28	0.4856	1.68e-04	1.636	0.4850
ISX	16.5	4.16	0.6138	1.81e-03	5.155	0.6144
Kaolinite	Data could not be fit to equations.					
Montmorillonite	0.193	3.68	0.5645	5.19e-04	4.2.62	0.6135
Peat Moss	0.211	1.54	0.9835	7.07e-05	9.207	0.9731
Seaweed #2	14.0	2.17	0.9969	3.51e-04	4.1179	0.9770
Zeolite	0.774	8.13	0.3116	5.32e-02	1.55	0.1682

## Zeolite

### Characterization

#### Cation Exchange Capacity

Average TCEC for the three particle size ranges of zeolite ranged from 7.5 to 10.7 meq/100g. Surface charge density and average TCEC for each size range are given in Table 4.7. The measured TCEC is well below that indicated for commercially available zeolite, which is estimated at about 180 -220 meq/100g. This may indicate that the material used in this study was less homogeneous than commercially available materials, or may reflect the effect of the relatively large particle sizes utilized.

Table 4.7. TCEC and Surface Charge Density for South Dakota Zeolite		
Particle Size (mm)	Average TCEC (meq/100g)	Average Charge Density (#charge/m <sup>2</sup> )
0.5-1.0	10.2	2.05E25
1-4	7.5	1.47E25
2-4.7	10.7	2.08E25

#### Surface Area

Average specific surface for each particle size range is given in Table 4.8. Surface area was uniform between the size ranges tested. This was an unexpected result, because small particle sizes would normally be expected to have significantly higher total surface area. Because surface area was uniform, material used in continuous flow operations can be selected based on the most desirable flow properties for the application without a significant loss in expected capacity.

Table 4.8. Average Specific Surface Area for South Dakota Zeolite	
Particle Size (mm)	Specific Surface Area (m <sup>2</sup> /g)
0.5-1.0	29.76
1.0-4.0	30.04
2.0-4.7	30.72

## Batch Studies

### Kinetic Studies: Synthetic Solutions -

Batch Test #5. The kinetic study conducted with the unwashed zeolite demonstrated that, for Pb, Cu and Zn, sorption kinetics are quite rapid. For Pb, 98 to 99.9% was sorbed after 15 minutes; for Cu, 99.4% and for Zn, 95.3 to 97.3%. The total pH change recorded for the Pb solution was approximately 2.5 units. The initial pH was 5.65; final pH was 8.1 to 8.2. The pH change recorded in the first 15 minutes was only 0.6 units, measuring 6.23 at the end of this time interval. The pH did not rise above 7 until after four hours of contact time. The percent removal of Pb is therefore attributed predominantly to sorption. The pH change for the Zn solution was greater and more rapid, measuring 7.96 at 15 minutes, and 9.17 to 9.22 at 30 hours. The pH change for the Cu solution was also rapid, measuring 7.96 at 15 minutes, from an initial pH of 5.33. pH rise was consistent for both solutions over the time period tested. Percent removal fluctuated slightly for both metals, but was relatively uniform for all particle sizes. Results are summarized in Appendix A, Tables A.1, A.2 and A.3, and Figures 4.15, 4.16, 4.17 and 4.18.

### Kinetic Study: Picatinney Extract -

Batch Test #4. In the kinetic study using acid washed zeolite and the Picatinney extract, less Pb and Zn was sorbed from solution and the kinetics were slower, than for the synthetic solutions and unwashed zeolite. Lower sorption is primarily attributed to hydrogen ion competition, as the pH of the Picatinney solution remained low for the duration of the study, but may also have been due to competition from other metals present in the extract. Pb and Zn appeared to have been preferentially absorbed over Cu. Initially, Zn sorbed more rapidly than Pb. However, it appears that the zeolite has a higher affinity for Pb because as solution concentration of Pb decreased, the solution concentration of Zn increased. Results are summarized in Appendix A, Table A.4, and Figures 4.19 and 4.20. Change in pH with time reflects the pH measured from individual samples contacted with the extract for the respective periods of time indicated.

### Equilibrium Batch Tests: Synthetic Solution -

Batch Test #1. The first equilibrium batch study was conducted with unwashed zeolite and a synthetic solution of  $\text{Pb}(\text{NO}_3)_2$  at an initial measured Pb concentration of 33,305 mg/l. To achieve this concentration, the initial solution pH was lowered to 2.1 using concentrated nitric acid. Highest Pb capacity was 575 mg/g. Highest Pb removal was 94.1% at 209.0 mg/g for the 15g sample of 1.0-4.0mm unwashed zeolite. Next highest was 91.6% at 202.9 mg/g for the 15g sample of 2.0-4.7mm UW zeolite. Overall removal for the smallest particle size range, 0.5-1.0mm, was lower than for the larger particle sizes. Capacity of the fine material was comparable (426 mg/g), although trends were not consistent. Results for this batch study are summarized in Table A.5 and illustrated graphically in Figure 4.21.

Batch Test #2. Due to problems with solubility of the  $\text{Pb}(\text{NO}_3)_2$  used for making up the solutions for Batch Test #2,, Pb concentrations in solution were lower than for the first equilibrium batch study. The unwashed zeolite batch study was therefore repeated so that the solution concentrations for both acid washed and unwashed zeolite would be comparable. The initial measured Pb concentration used for the acid washed zeolite was 17,738 mg/l; for the unwashed zeolite, the Pb concentration was 14,087 mg/l.

The highest Pb removal obtained was 68.9% at 80.7 mg/g for the 15g sample of 0.5-1.0 mm acid washed zeolite. Approximately 60% removal at 70.6 mg/g was obtained for the 15g sample of 1.0-4.0 mm acid washed zeolite and for the 15g sample of 0.5-1.0 mm unwashed zeolite at 56.9 mg/g. The general trend indicates that the finest material has approximately 20% higher removal than the coarsest, for both washed and unwashed zeolite. Removal by the mid size material fell between these two. The highest measured capacity was 366.2 mg/g for the 1g sample of the 1.0-4.0mm acid washed zeolite. Next highest capacity was 331.1mg/g for the 1g sample of the 0.5-1.0 mm acid washed zeolite. These values were approximately 5 times and 2 times greater than for the corresponding mass and particle size of unwashed zeolite, respectively.

For most other corresponding mass and particle size ranges, the capacity was within the same order of magnitude for acid washed and unwashed material. The results for the equilibrium batch test for both acid washed and unwashed zeolite are summarized in Appendix A, Table A.6 and are presented here in Figures 4.22 and 4.23.

### Equilibrium Batch Test: Picatinney Extract -

Batch Test #3. Highest Pb removal for the Picatinney extract using 2.0-4.7mm acid washed zeolite was 80.5% at 0.07 mg/g. Highest Pb capacity was 0.32mg/g for the 1g sample. Maximum removal of Zn was 7.1% at 0.06mg/g which was also the maximum capacity. Maximum Cu removal was 12.6% at 0.04 mg/g and maximum capacity of 0.51 mg/g. Low sorption capacity may be attributable to hydrogen ion competition due to the low pH, or to competitive sorption from other metals in solution. Analysis for other metals was not conducted. Results for the 2 hour contact time are summarized in Appendix A, Table A.7 and Figure 4.24-

4.26. The test was repeated with a 24 hour contact time with no significant improvement in sorption. This data has not been included.

#### Equilibrium Batch Test: FBH Extract -

Batch Test #7. The percentage of lead removed from this extract was higher than the percentage of zinc or copper. The order of removal was  $Pb > Zn > Cu$ . Maximum Pb removal was 98.8% at a capacity of 2.76 mg/g. Highest Pb capacity was 26.3 mg/g sorbent, which gave a removal of 77.2 percent. Highest zinc removal was 79.7% at a capacity of 0.011 mg/g. Highest copper removal was 66.4% at a capacity of 0.03 mg/g. Results are summarized in Appendix A Table A.8 and Figures 4.27-4.29.

#### Selectivity Tests

Batch Test #6. Results of the selectivity test indicate that Pb sorption was relatively unaffected by varying Ca concentrations. Conversely, sorption of Ca was influenced by Pb concentration, and was lowest for high Pb concentration and 2 hr contact time. Slightly higher Pb removal was obtained for the 24 hour contact time than for the 2 hour contact time. Results are summarized in Appendix A Table A.9, and Figures 4.30 and 4.31.

#### Model Parameters

Linear and non-linear regression was performed on the equilibrium data, for fit of Langmuir and Freundlich models introduced previously in the discussion of the screening study results. A summary of the parameters obtained for Pb sorption is given in Table 4.9. Parameter values are quite varied, and  $R^2$  values indicate that neither the Freundlich or the Langmuir are consistently good descriptors for the data. Because of the typically poor correspondence between parameters obtained from batch studies and column studies respectively, more reliable scale-up parameters may be obtained from analysis of column performance.

Kinetic data was plotted to determine order of reaction. For the synthetic Pb solution, only the data from the first 30 minutes could be satisfactorily fit, indicating a first order reaction with  $R^2$  of 0.944. Highest correlation for the Picatinney data was for a second order reaction, with  $R^2$  of 0.866.



Table 4.9 Summary of Model Parameters for Equilibrium Data							
Test Number	Particle Size	Freundlich			Langmuir		
	(mm)	K	n	r <sup>2</sup>	K	x <sub>m</sub>	r <sup>2</sup>
Batch #1	0.5-1.0	4.9E-15 <sup>a</sup>	0.260	0.450	N/A <sup>c</sup>		
	1.0-4.0	N/A <sup>c</sup>			N/A <sup>c</sup>		
	2.0-4.7	N/A <sup>c</sup>			N/A <sup>c</sup>		
Batch #2-AW	0.5-1.0	0.02 <sup>a</sup>	1.05	0.624	6.49E-5 <sup>a</sup>	294.12	0.648
	1.0-4.0	3.2E-5 <sup>a</sup>	0.614	0.646	5.49E-6 <sup>b</sup>	2688	0.268
	2.0-4.7	2.1E-4 <sup>a</sup>	0.741	0.865	9.0E-7 <sup>b</sup>	6861.1	0.679
Batch #2-UW	0.5-1.0	4.4E-10 <sup>b</sup>	0.774	1.0	6.1E-7	17500	0.864
	1.0-4.0	0.623 <sup>a</sup>	1.972	0.491	6.7E-5 <sup>a</sup>	166.67	0.640
	2.0-4.7	N/A <sup>c</sup>			N/C <sup>c</sup>		
Batch #3	2.0-4.7	0.0302 <sup>b</sup>	0.956	0.996	2.3E-5 <sup>b</sup>	1445	0.994
Batch #7	2.0-4.7	1.14 <sup>b</sup>	1.45	0.996	5.17E-03 <sup>a</sup>	106.38	0.995

- a Parameters obtained by linear regression  
 b Parameters obtained by non-linear regression  
 c Satisfactory fit could not be obtained with either linear or non-linear regression

## Column Studies

### Influent -

Influent concentrations displayed very little variation over the course of the column studies; most concentration differences fell within normal analytical deviation for duplicate samples. Since influent samples were not duplicates, but discrete samples taken at intervals from the influent tubing, slight variation in dissolved concentrations could be expected as a result of matrix interference or very fine suspended solids within the extract. An average influent concentration was determined for all analytes from the influent samples for each column. These average values were used in the calculation of normalized effluent concentrations. Measured influent concentrations were in the range of 400-450 mg/l Pb. Zn and Cu concentrations were approximately 2.5 and 7.0 mg/l respectively. Influent pH was within  $4.5 \pm 0.06$ .

### Column #1 -

Column #1 was the control column. Extract was run through the control column for 12 hours with an empty bed and all fittings in place. Influent and effluent was sampled at 0,4,8 and 12 hours. Concentration differences across the column ranged from 0.4 to 9.6%. This difference is within the normal acceptable analytical variation between duplicate samples. Losses in the column apparatus were therefore considered negligible.

### Column #2 and #3 -

Columns 2 and 3 were packed with 2.0-4.7 mm UW and AW zeolite respectively and run at 3 BV/hr (60 ml/min) for a period of 12 hours. Influent was sampled at 0,3,6,9 and 12 hours. Effluent was sampled continuously. Breakthrough curves (BTC) for Pb, Zn and Cu are given in Figures 4.32 and 4.33. Bulk density of the material packed in Column 2 was  $0.217 \text{ g/cm}^3$ , and in Column 3 was  $0.233 \text{ g/cm}^3$ .

### Columns #4 and #8 -

Columns 4 and 8 were packed with 2.0-4.7 mm UW and AW zeolite respectively and run at 1.0 BV/hr (20 ml/min). Column 4 was run for 12 hrs and Column 8 for 15 hrs. Influent was sampled at 0,3,6,9 and 12 hrs. Bulk density of material in Column 4 was  $0.231 \text{ g/cm}^3$ , and in Column 8 was  $0.205 \text{ g/cm}^3$ . Breakthrough curves (BTC) for Pb, Zn and Cu are given in Figures 4.34 and 4.35.

#### Columns #6 and #7 -

Columns 6 and 7 were loaded with 2.0-4.7 mm UW and AW zeolite respectively and run at 0.3 BV/hr (6ml/min) for a period of 12 hours. Influent was sampled at 0,3,6,9 and 12 hours. Bulk density of material in Column 6 was 0.211 g/cm<sup>3</sup>, and for Column 7 was 0.200 g/cm<sup>3</sup>. Breakthrough curves (BTC) for Pb, Zn and Cu are given in Figures 4.36 and 4.37.

#### Column #5 -

Column 5 was loaded with 2.0-4.7 mm AW zeolite and run at 1 BV/hr (20ml/min) for a period of 14 hours, with a 2 hour flow interruption at 4 hours. Influent was sampled at 0,3,6,9 and 12 hours. Bulk density of the material packed in Column 5 was 0.219 g/cm<sup>3</sup>. Breakthrough curves (BTC) for Pb, Zn and Cu are given in Figure 4.38.

#### Column #9 -

Column 9 was packed with 2.0-4.7 mm UW zeolite and run at 0.3 BV/hr (6 ml/min) for a period of 7 days. Influent was sampled once daily on days 1,2,3, and 4. Effluent was sampled at 0,24,48,72,96,120,144 and 166 hours. Bulk density of the material packed in Column 9 was 0.203 g/cm<sup>3</sup>. Breakthrough curves (BTC) for Pb, Zn and Cu are given in Figure 4.39

#### Column #10 -

Column 10 was packed with 0.5-1.0 mm UW zeolite and run at 0.3 BV/hr for a period of 12 hours. Influent was sampled at 0,3,6 and 9 hours. Effluent was sampled continuously. Bulk density of the material packed in Column 10 was 0.211 g/cm<sup>3</sup>. Breakthrough curves (BTC) for Pb, Zn and Cu are given in Figure 4.40.

#### Effluent pH -

Effluent samples were tested for pH. Effluent pH was initially near, or slightly above 7.0, but dropped rapidly for both UW and AW zeolite. Change of pH with time is reflected in Figure 4.41.

#### Curve Fitting -

Data from the column studies was manually fitted with the one-dimensional convective-dispersive solute transport equation using an analytical solution for the appropriate initial and boundary conditions (Van Genuchten and Alves 1982). Because a chloride study was not conducted for determination of a dispersion coefficient, a value of 1E-08 was assumed based on published values for coarse materials. The retardation factor was varied until a good visual correspondence was obtained. For the low flow columns (0.3 BV/hr), relatively good correspondence was obtained for a retardation factor (R) value of 21. More divergence was

evident for the 1.0 BV/hr columns, with the model under predicting breakthrough. The closest correspondence was obtained with a retardation factor of 8.5. The high flow rate columns (3 BV/hr) were not well represented by the model. Column 7, 8 and 2 illustrate in Figures 4.42 - 4.44.

## V DISCUSSION

### Limitations of the Data

#### Screening Studies

AA analysis of mercury standards gave concentrations much lower than the calculated solution concentrations. The results were verified using the EPA standard method for mercury analysis Method 7470A (SW-846, 1982). Possible filter absorption of the metals was evaluated by analyzing 1000mg/L solutions of Cd, Cr, Pb and Hg before and after filtering. No significant absorption could be attributed to the filters. It was therefore concluded that low analytical concentrations of mercury may be due to volatilization. Because the initial concentration was taken to be the measured concentration of the blank sample after tumbling, which should have experienced the same volatilization as the samples, this is not expected to have significantly affected the data.

Other mechanisms potentially affect indicated metals sorption. Higher than actual sorption capacities may be caused by precipitation facilitated by the acetate contained in the buffer, pH changes and subsequent hydroxide precipitation in unbuffered, or poorly buffered, samples, and complexing of metals in solution which cannot be detected by the AA. Lower than actual sorption capacity would result from competitive sorption of the  $\text{Na}^+$  contained in the buffer. The isotherms developed from the batch studies, therefore, may not be representative of sorption alone.

Many of the samples were highly concentrated and required dilution to within the calibration range of the AA. Small dilution errors could potentially introduce large errors in the extrapolated results.

#### Zeolite Studies

Some inconsistency was noted in the capacity trends of the equilibrium batch studies both for synthetic solutions and the Picatinney extract. This is thought to be principally attributable to the natural heterogeneity of the sorbent. Review of QA/QC data for both batch and column studies indicates possible matrix interference for some samples. Duplicates and quality control samples were consistently within acceptable ranges. Spike recoveries were somewhat variable, however. Samples were re-run on AA to confirm results and selected samples were analyzed by ICP to resolve the problem. Because this was observed for both synthetic solutions and soil extracts, this is attributed to the zeolite, which may have released ions affecting the analysis of the metals in question. Overall, the data followed smooth trends and was consistent with expected system performance. Differences in AA and ICP results appear to be within the magnitude of variation that would be expected due to natural heterogeneities of this material. Given the consistency of the data, and after reviewing test results for effects of the interference, it is thought

that capacity calculations based on this data are reliable and representative for the material used in this study.

## **Analysis of Results**

### **Screening Study**

Maximum sorption capacities for Pb were 368.2 mg/g for zeolite, 270.9 mg/g for ISX and 241.8 mg/g for Seaweed #2. These results are consistent with Freundlich sorption parameters for ISX and Seaweed #2, although the correlation coefficient for ISX was not high. Maximum capacity for Cr and Cd was 80.5 mg/g and 194.2 mg/g respectively, for zeolite. Maximum capacity for Hg was 277.3 mg/g for activated carbon.

Selectivity sequences for zeolite, and seaweed #2 indicate a preference for Pb over other metals. The remaining sequence was Hg>Cd>Cr for seaweed #2, and Cd>Cr>Hg for zeolite. ISX demonstrated a preference for Hg over Pb, followed by Cd and then Cr.

### **Zeolite Batch Studies**

Results of the batch studies indicate a selectivity for Pb over Cu and Zn for both the synthetic solutions and the soil extracts. Highest demonstrated capacity for Pb was 574.7 mg/g obtained for the unwashed zeolite in Batch Study #1 using a synthetic solution. Sorption using the FBH extract and the Picatinney extract was much lower. Highest Pb capacity for the Picatinney extract was 0.32 mg/g and for the FBH extract was 26.3 mg/g.

Results of the selectivity test indicate that Pb sorption was relatively unaffected by the Ca concentration, with over 99% removal of the lead over 24 hours at both high and low relative Ca concentrations.

### **Zeolite Column Studies**

For all the columns, Pb transport was markedly more retarded than for Cu and Zn. At the highest flow rate (3.0 BV/hr), all analyte effluent concentrations rose rapidly to near the influent concentrations. This suggests that significant flow along the sidewalls may have occurred, bypassing the sorbent, or that the retention time was insufficient for significant sorption to take place. For the UW zeolite, at 1.0 BV/hr and 0.3 BV/hr, Pb removal was 25% and 78% higher than for the high flow rate respectively. For the AW zeolite, Pb removal as compared to the high flow rate was unchanged for the 1.0 BV/hr flow rate and 81% higher for the 0.3 BV/hr flow rate. Differences in Cu and Zn removal were less dramatic. For the UW material, 12 hour effluent Cu concentrations were 8% and 16% lower for the 1.0 BV/hr and 0.3 BV/hr flow rates respectively. Similarly, twelve hour Zn effluent concentrations were 11% and 27% lower. For the AW material, 12 hour effluent Cu and Zn concentrations were virtually unchanged, and in some cases

slightly higher. There was a 26% higher removal of Zn for the lowest flow rate, however, as compared to the 3.0 BV/hr flow rate.

These results indicate that, for the AW material, flow rate did not significantly affect Cu and Zn removal. This may be because Cu and Zn removal was not high overall as compared to Pb. Differences in Cu and Pb removal apparently attributable to acid washing the material were highest for the high flow rates. Pb removal was 28% higher for AW over UW at 3.0 BV/hr, 5% higher at 1.0 BV/hr and 18% higher at 0.3 BV/hr. Cu removal was 28% higher for AW over UW material at 3.0 BV/hr, 18% higher at 1.0 BV/hr and 4% higher at 0.3 BV/hr. Zn removal was 2% higher for AW over UW at 3.0 BV/hr, 20% higher at 1.0 BV/hr and 8% higher at 0.3 BV/hr.

Results of the stop flow study indicate that sorption is kinetically limited (Column 5). Effluent concentrations dropped from 138.3 mg/l Pb ( $C_e/C_o=0.32$ ) to 48.6 mg/l Pb ( $C_e/C_o=0.11$ ) after a two hour period of flow cessation. Cu and Zn effluent reductions were 12% and 22% respectively. Results of the seven day study indicate that, at 0.3 BV/hr, the zeolite was exhausted ( $C_e/C_o=0.95$ ) at approximately 166 hours, based on the Pb breakthrough curve.

Comparison of the results of the low flow study using the 0.5-1.0 mm UW zeolite to the highest removal obtained with the larger material indicates a significantly higher Pb removal at 12 hours ( $C_e/C_o=0.00$  vs 0.12). Cu removal was only slightly improved, however, and Zn removal was approximately 10% less than for the larger material at 12 hours.

#### Volume Reduction Analysis -

Analysis of the results obtained for Columns 9 and 10 give some indication of the volume of liquid that could be treated to specified limits. Effluent Pb concentrations for Column 9 did not rise above 10 mg/l until after 24 hours. This represented a total volume of 8.6 liters indicating a treatment capacity for this effluent concentration and flowrate of approximately 34.4 l/kg. Effluent Pb concentrations for Column 10 were at or below detection for the 12 hour duration of the study. This represented a total volume of 4.3 liters. Capacity based on this volume does not reflect the total capacity of the sorbent, since the duration of the study was insufficient to develop breakthrough. Capacity calculations based on this volume can be taken to be a very conservative estimate of the material capacity, and preliminary volume reduction analysis conducted using these values. Treatment capacity based on a total volume of 4.3 liters and zero Pb concentration in effluent, is 16.7 l/kg zeolite, or 7.1 mg Pb/g zeolite.

The specific gravity of clinoptilolite ranges from 1.5 g/cm<sup>3</sup> for reagent grade zeolite, to between 2 to 2.4 g/cm<sup>3</sup> for the naturally occurring mineral. Assuming a SG of 2.0, and a sorption capacity based on the total volume of extract treated in Column 10, treatment of 1000 liters of extract at 425 mg/l Pb would result in a volume reduction of 97% (1000 liters extract vs 30 liters zeolite) or a weight reduction of 94% (approximately 1000 kg extract vs 60 kg zeolite). Natural zeolite is available for approximately \$94./Mg (\$85.-100./short ton), or \$0.18/kg (\$4./50 lb) in smaller quantities, plus freight. Disposal in a hazardous waste landfill is estimated at approximately \$50./200 liters. For the example developed here, and assuming a single use, zeolite

cost would be approximately \$5.60-\$10.60/1000 liters influent. Disposal cost would be \$7.50 for 30 liters of spent zeolite. This gives a total treatment cost of approximately \$13.-18./1000 liter, as compared to \$250./1000 liters to dispose of the extract directly, a 93 to 95% cost savings.

The cost to treat the same volume of this extract with a commercial ion exchange resin was also estimated. Because the resin was not tested with this waste, capacity was estimated based on published values for the resin, Amberlite IRC-718. Conditions at which the capacity of the resin was determined differ from those under which the capacity of the zeolite was determined, and this should be strongly considered in the final analysis. The capacity of the resin is based on a breakthrough value of 0.5 ppm Pb, for a waste stream containing 50 ppm Pb, as compared to zero breakthrough for a waste stream containing 425 ppm Pb for the zeolite. Flow rate was 8 bed volumes per hour for the resin, and 0.3 bed volumes per hour for the zeolite. A definitive cost comparison would require determining the ultimate capacity of the fine zeolite under low flow conditions (which would give a lower unit cost than that estimated here), and the actual capacity of the resin for the same extract and flow rates.

Capacity for the Amberlite resin is given as 3.6 lb/ft<sup>3</sup> for a 50 ppm Pb influent, 0.5 ppm breakthrough, 8 bed volumes per hour flow rate, at pH 4, as previously stated. Regeneration cost is estimated assuming 10 lb HCL at a concentration of 5% per cycle, and a resin life of 100 cycles. Purchase cost of the resin ranges from \$420. to \$435./ft<sup>3</sup>, with a minimum purchase requirement of \$1000.00. Estimated treatment cost for 1000 liters of soil extract using the Amberlite resin is approximately \$3.90/1000 liters. This cost estimate is contingent upon the following assumptions: the minimum purchase requirement is not a factor, and the total volume of extract treated over the life of the resin is 101,000 liters, thus distributing the capital cost of the resin over the total volume of extract that could be treated. If smaller volumes of wastewater were treated, the unit cost would be higher. For example, if only 1000 liters were treated, the unit cost would be approximately \$115.-\$1000/1000 liters, depending upon whether the minimum purchase requirement applies.



## VI CONCLUSIONS

The initial literature search and screening study identified several sorbents with good sorption capacity for lead, including zeolite, seaweed in the form of a feed supplement, and ISX. The highest capacity (368.2 mg/g) was demonstrated by the reagent grade zeolite. In multi-metal testing, both zeolite and seaweed were most selective for lead.

In subsequent testing to the commercial grade zeolite, the highest lead capacity demonstrated was 574.7 mg/g for the 1.0-4.0 mm UW material at initial Pb concentration of 30,000 mg/l. Kinetics of sorption appear to be relatively rapid, with over 99% of Cu and Pb, and 95-97% of Zn in the first 15 minutes of contact. Zeolite appears to demonstrate a very strong preference for Pb over Cu and Zn, and over Ca, even at high relative concentrations of Ca.

Results of the column studies indicate that, for the 2.0-4.7 mm material, acid washing of the zeolite does improve sorption characteristics. Comparison of the best results obtained in the column studies using the 2.0-4.7 mm material to the results obtained using the 0.5-1.0 mm material suggest that sorption is kinetically favored for the fine zeolite, which has a much higher capacity under continuous flow conditions at the low flow rate tested. Further capacity increases could potentially be developed by acid washing the fine zeolite. However, review of the batch studies does not indicate a consistently higher capacity for the fine zeolite over the coarser zeolite. It is likely that natural variations in the material may be partly responsible for the differences in performance, and that longer contact times will also minimize performance variation between particle sizes. Further column tests would need to be conducted to make a more definitive determination in this regard.

The volume reduction analysis indicates that significant mass and volume reduction can be achieved with zeolite in the treatment of liquid waste. Cost comparison to a commercial ion exchange resin indicates that for single use treatment of small volumes, zeolite is significantly more cost effective than ion exchange. At higher volumes, ion exchange is likely to be more cost effective if regenerated for multiple use cycles. This determination should be made by capacity testing of both sorbents for the specific waste stream. Further analysis should be directed at determining the ultimate capacity of the fine zeolite at low flow rates, the comparative performance of commercially available zeolite with a higher indicated CEC, and comparative costs of an ion exchange resin for treatment of the waste stream.

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## **FIGURES**

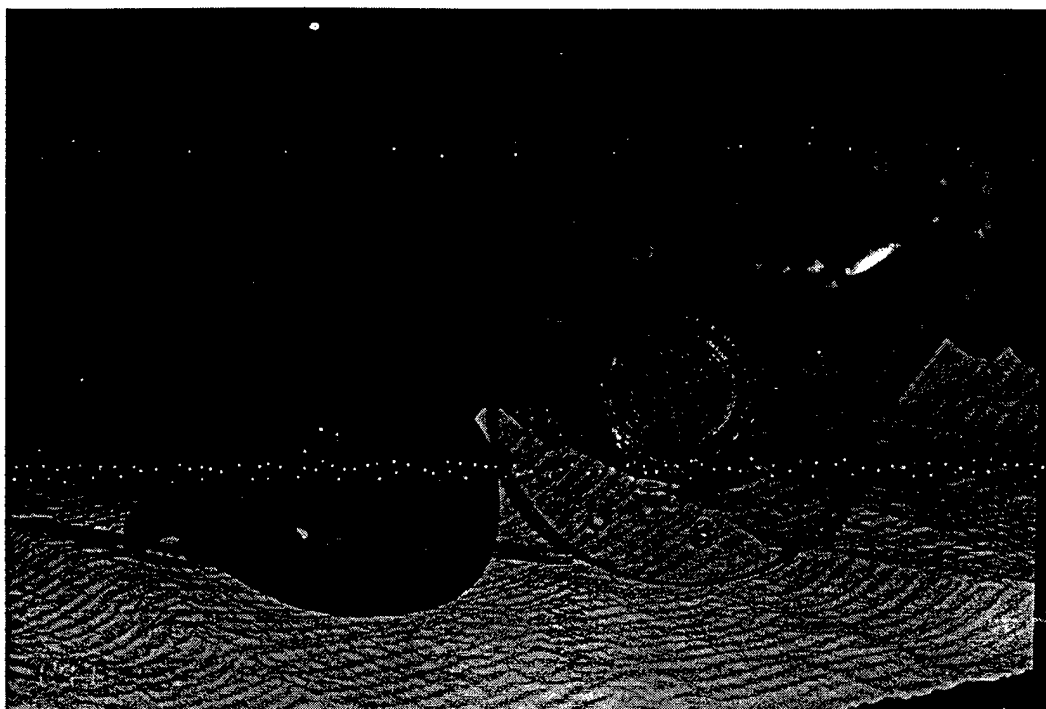


Figure 3.1 Column Setup

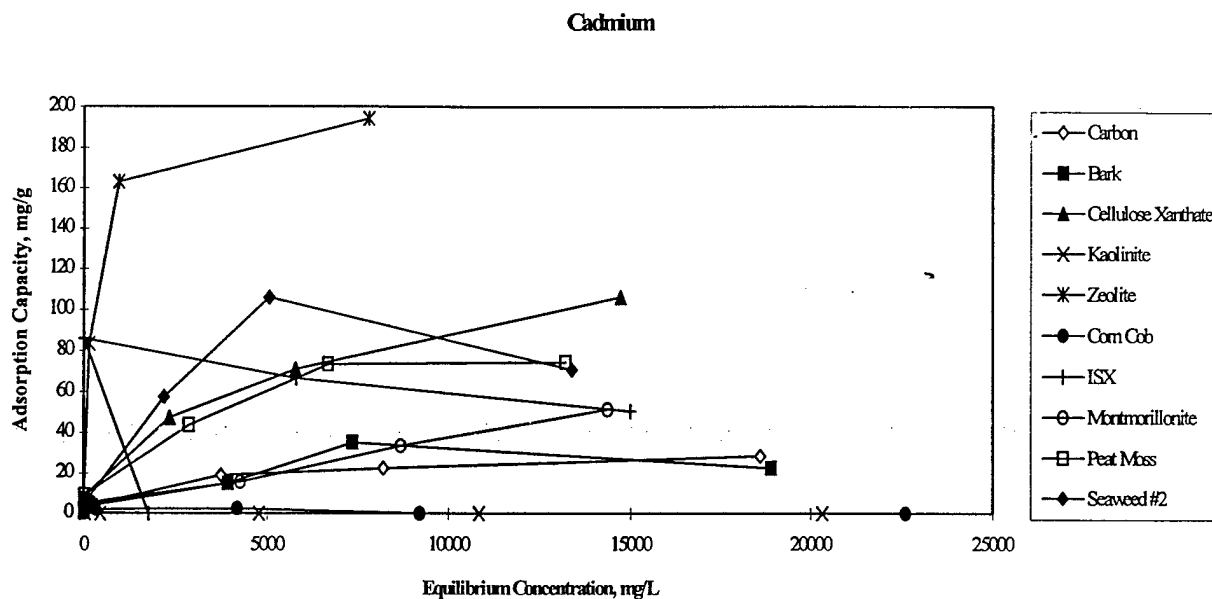


Figure 4.1 Cadmium Sorption Isotherms

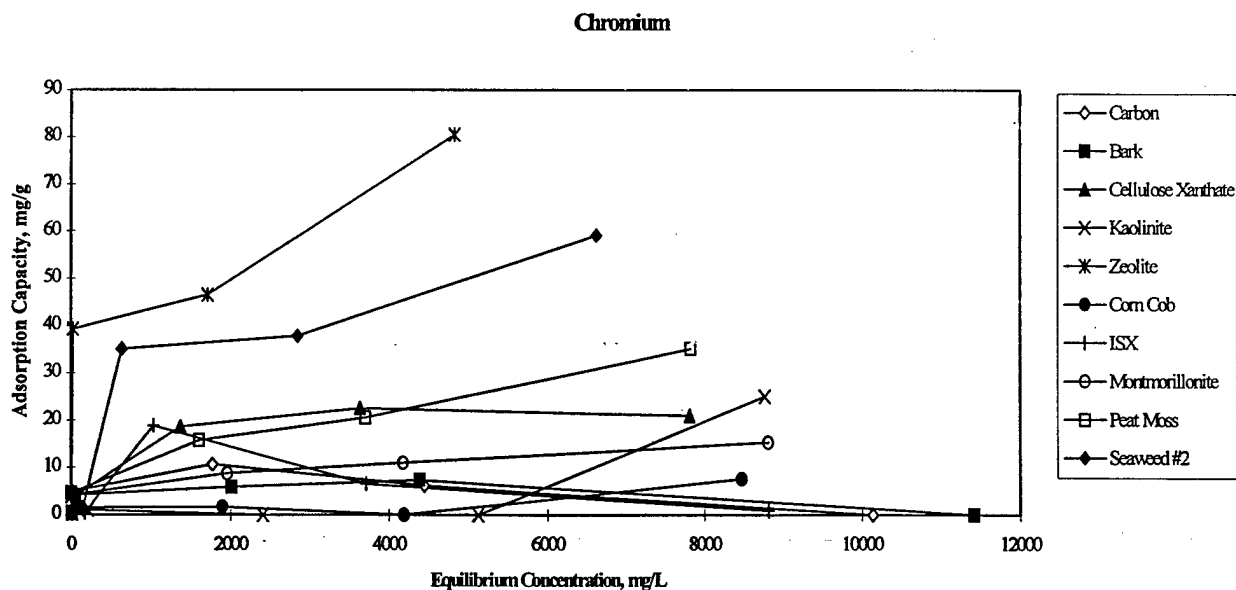


Figure 4.2 Chromium Sorption Isotherms

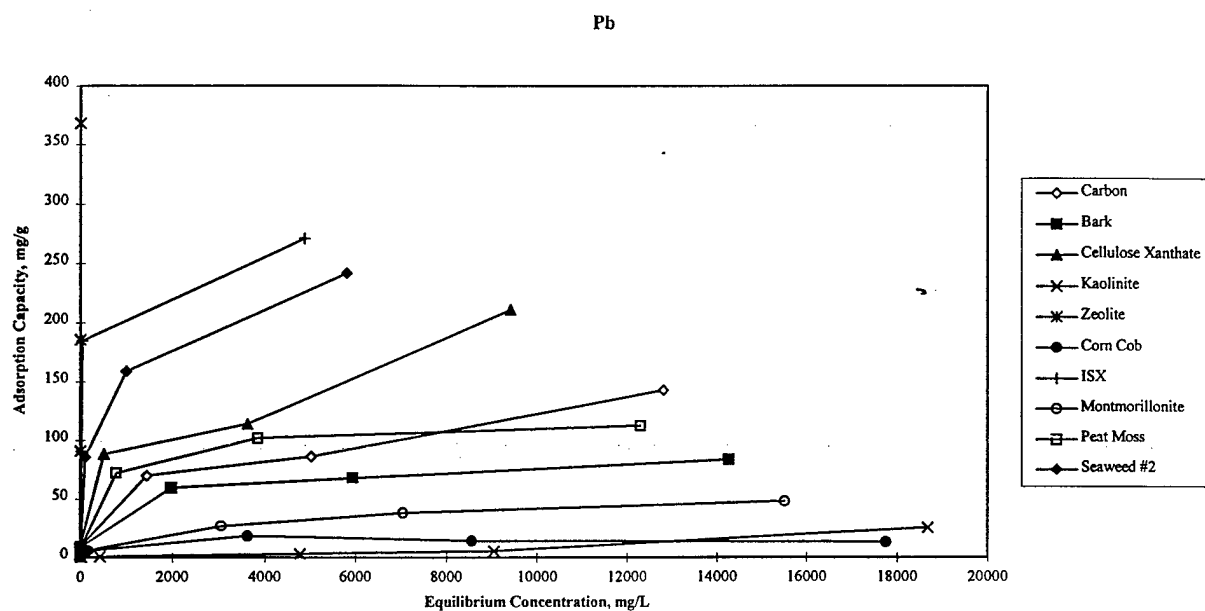


Figure 4.3 Pb Sorption Isotherms

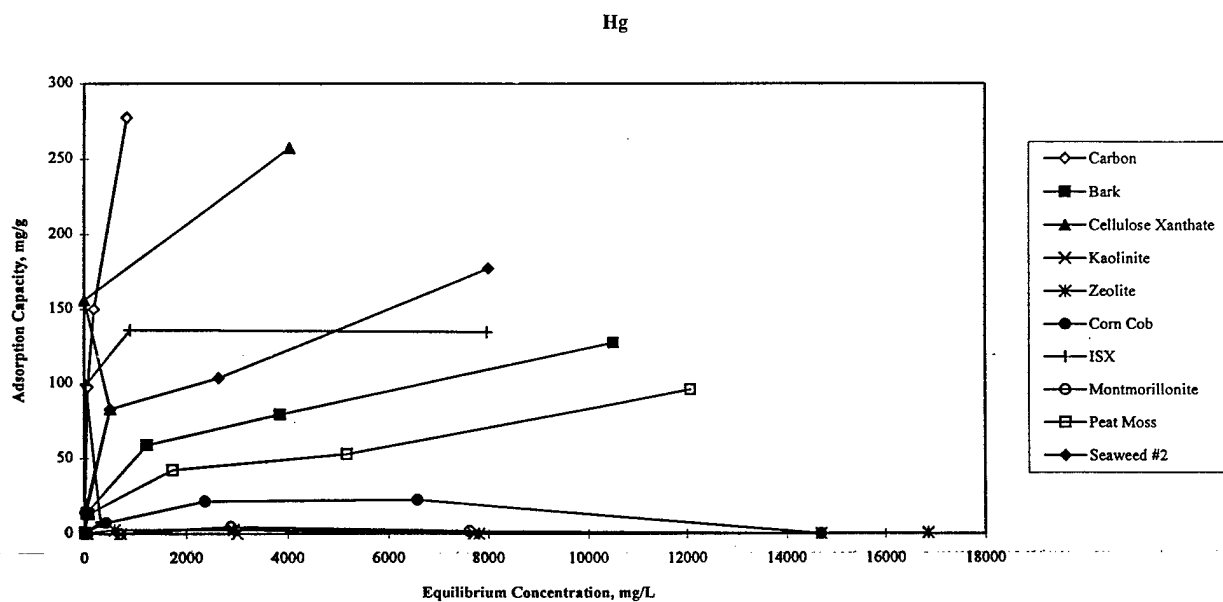


Figure 4.4 Hg Sorption Isotherms

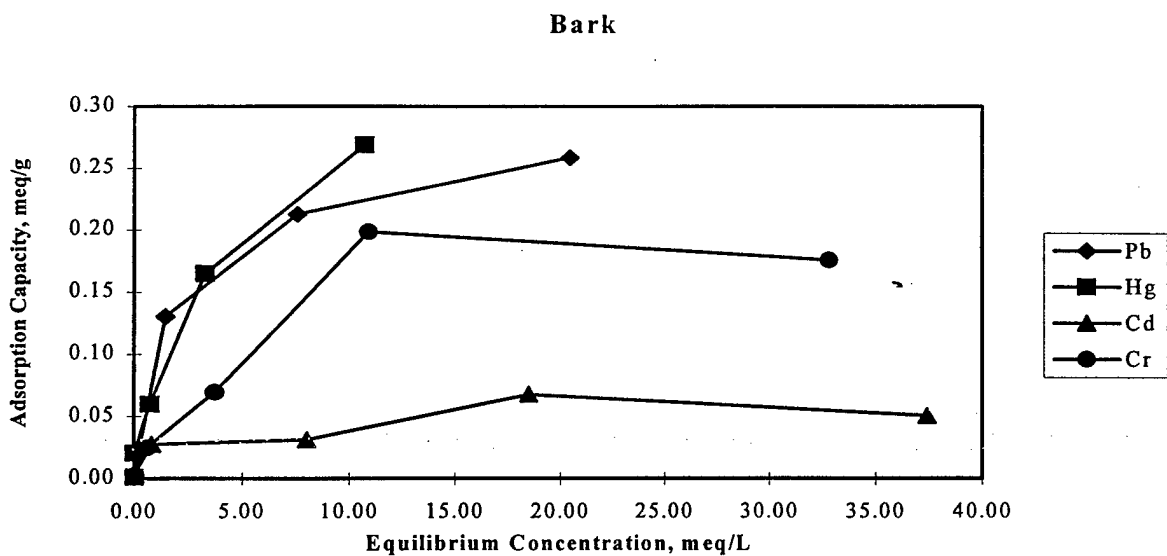


Figure 4.5 Bark Multi-Metal Sorption Isotherms

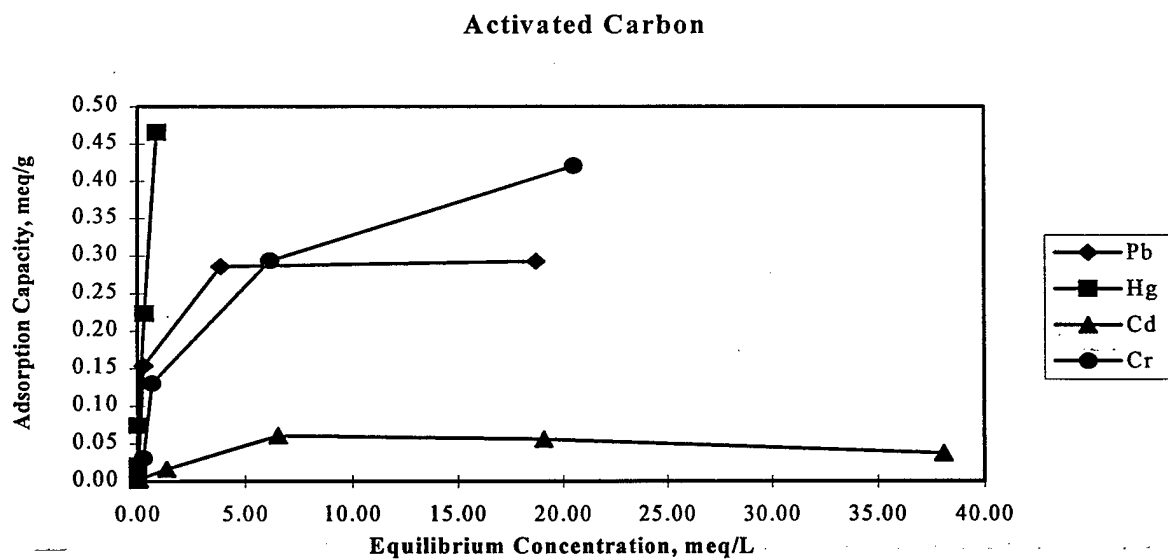


Figure 4.6 Activated Carbon Multi-Metal Sorption Isotherms

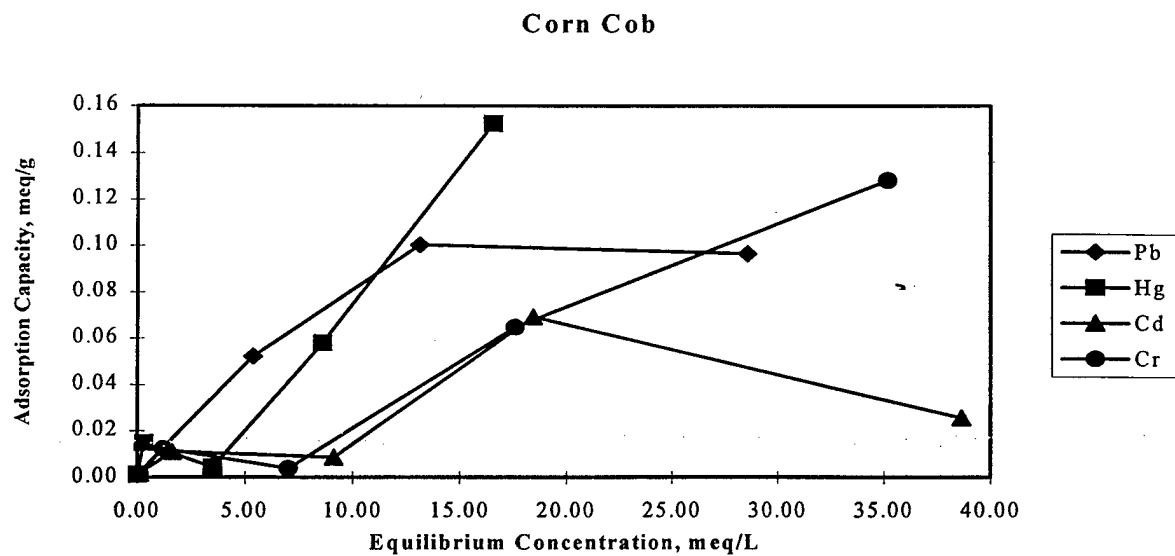


Figure 4.7 Corn Cob Multi-Metal Sorption Isotherms

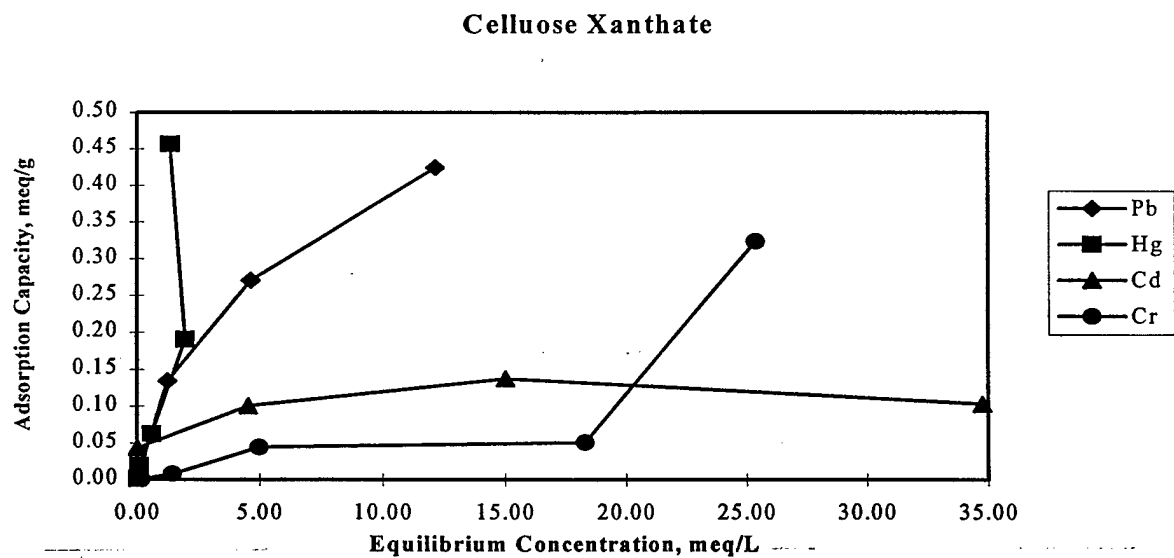


Figure 4.8 Cellulose Xanthate Adsorption of Four Metals in Solution



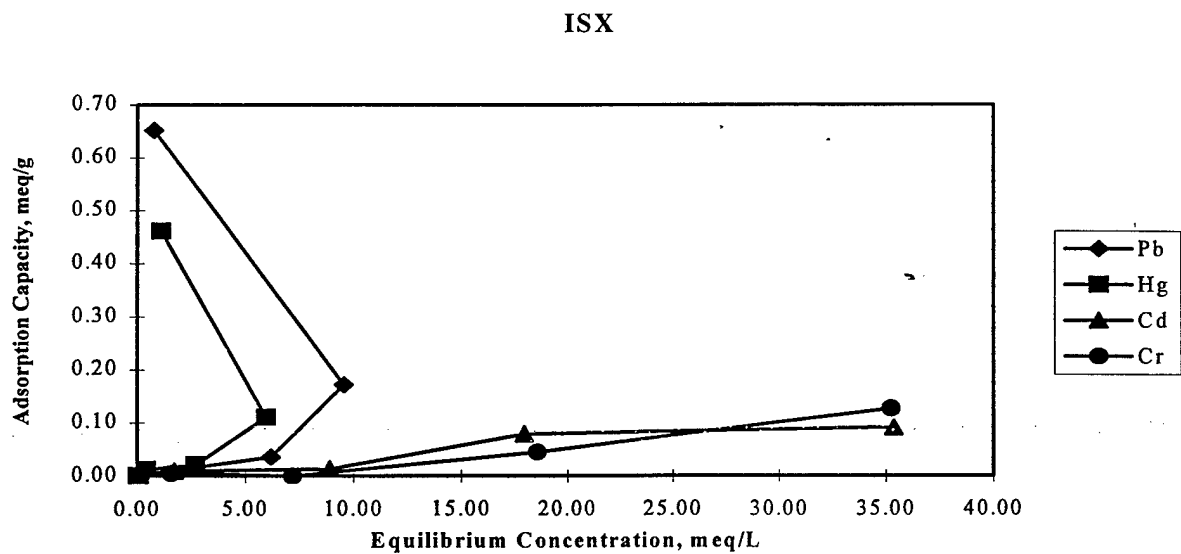


Figure 4.9 ISX Multi-Metal Sorption Isotherms

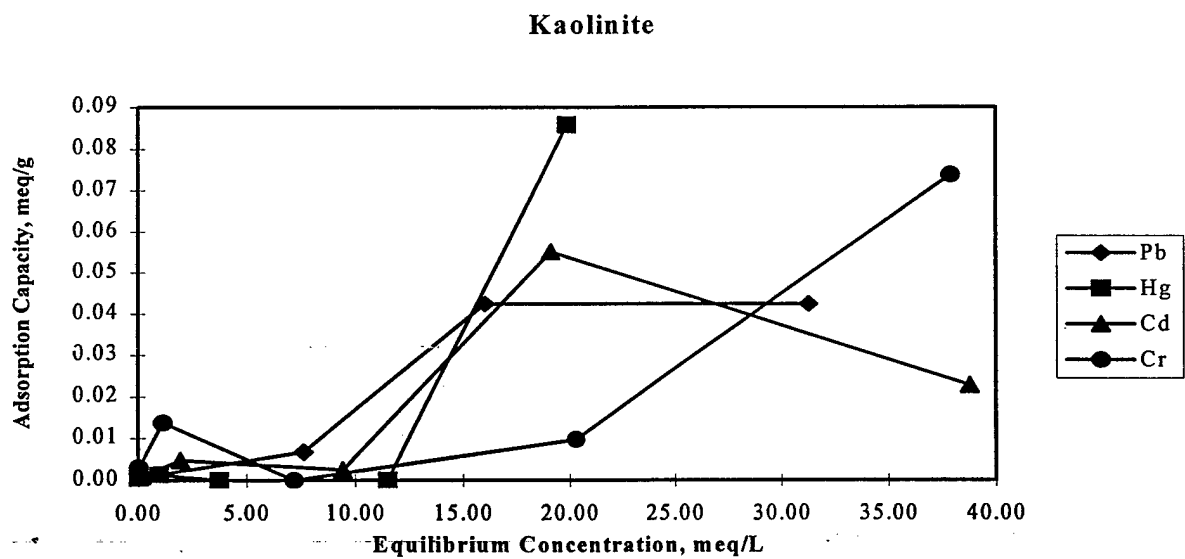


Figure 4.10 Kaolinite Multi-Metal Sorption Isotherms

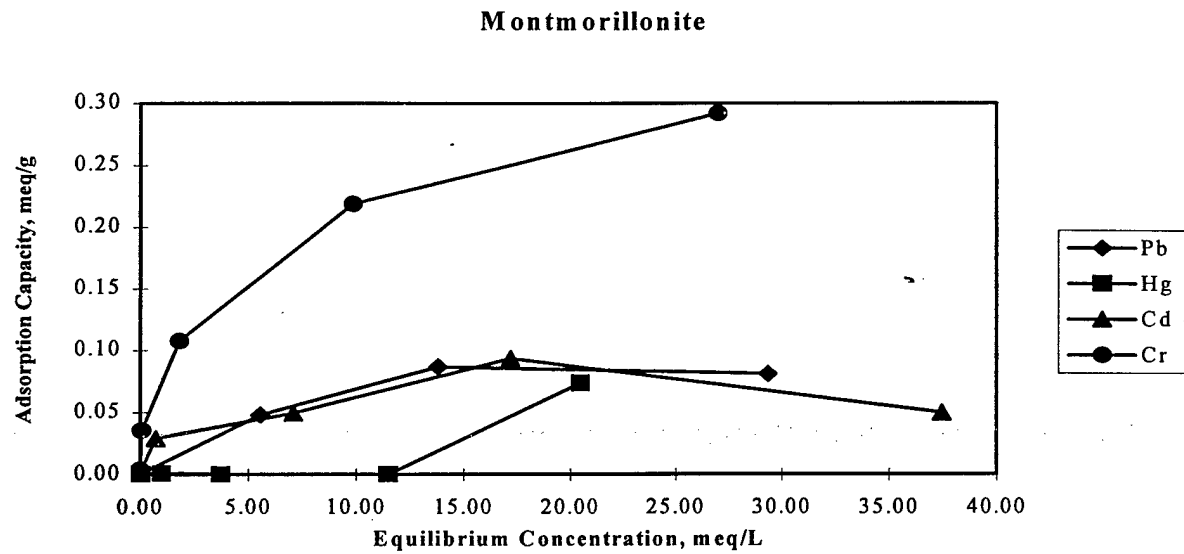


Figure 4.11 Montmorillonite Multi-Metal Sorption Isotherms

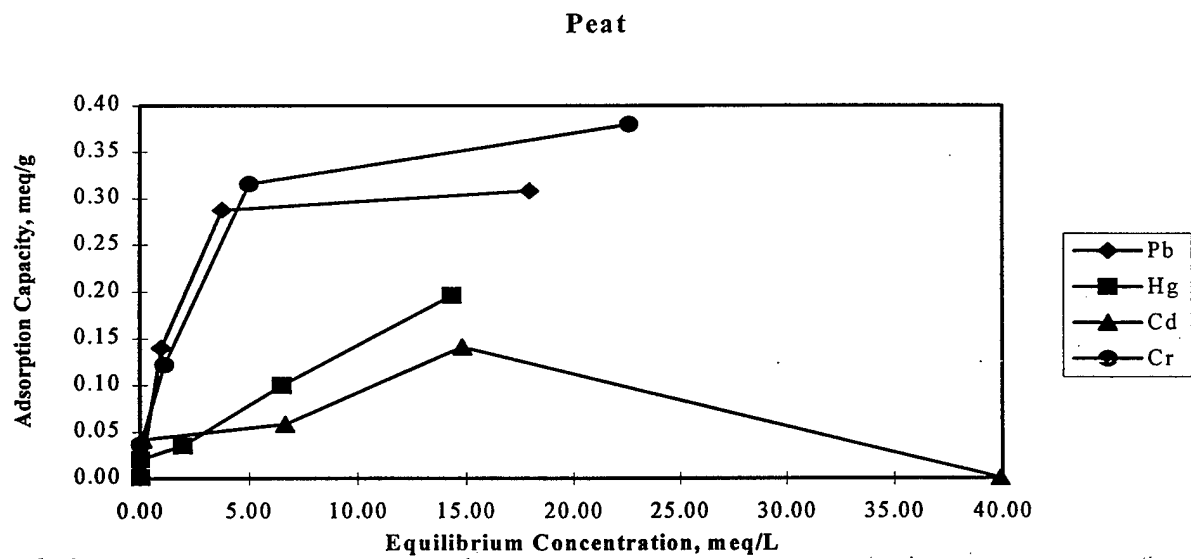


Figure 4.12 Peat Moss Multi-Metal Sorption Isotherms

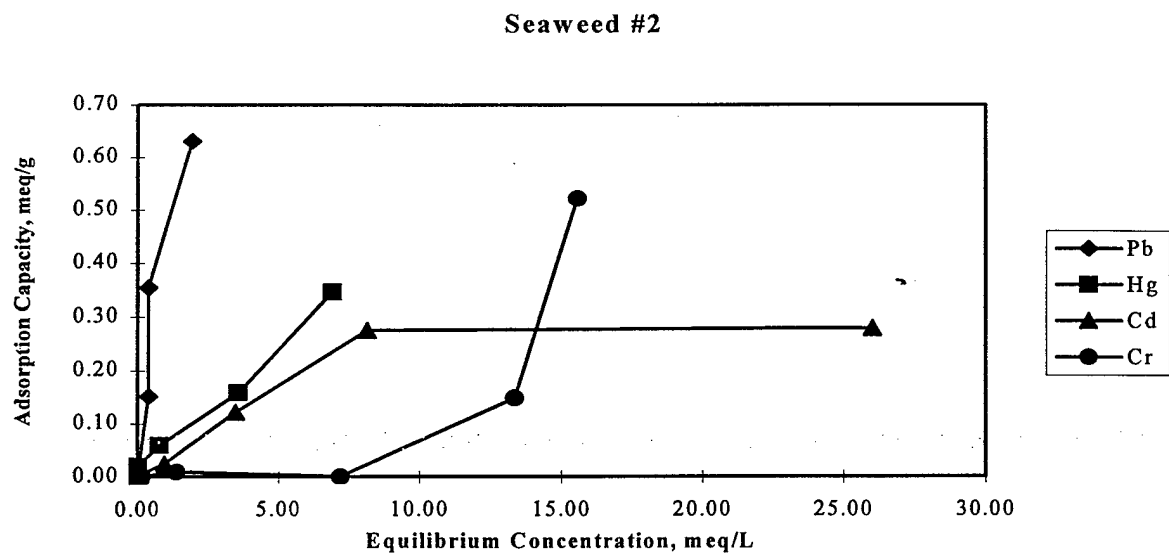


Figure 4.13 Seaweed #2 Multi-Metal Sorption Isotherms

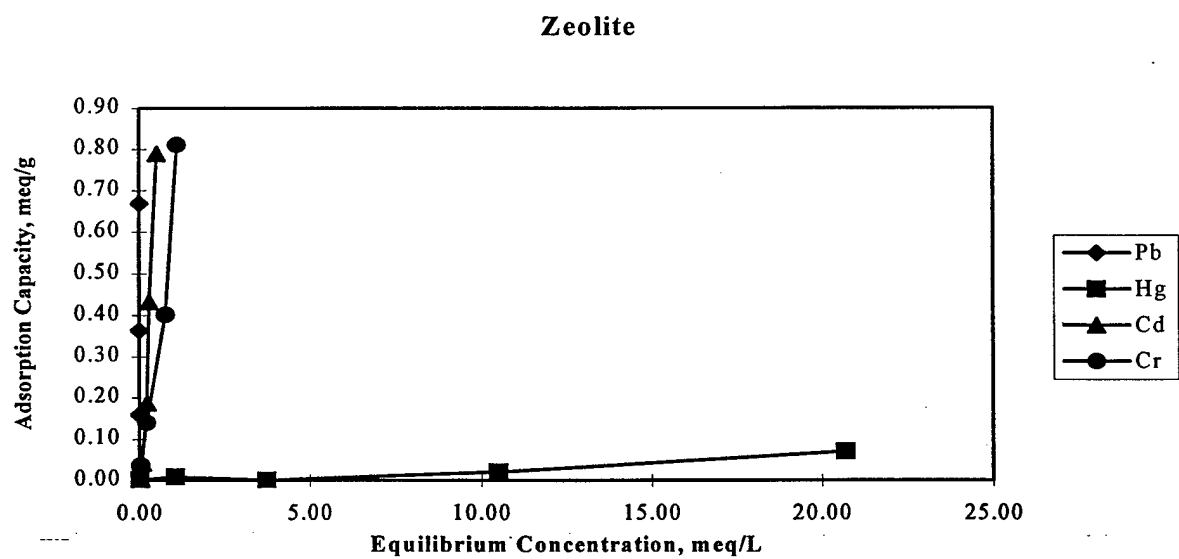


Figure 4.14 Zeolite Sorption Isotherms

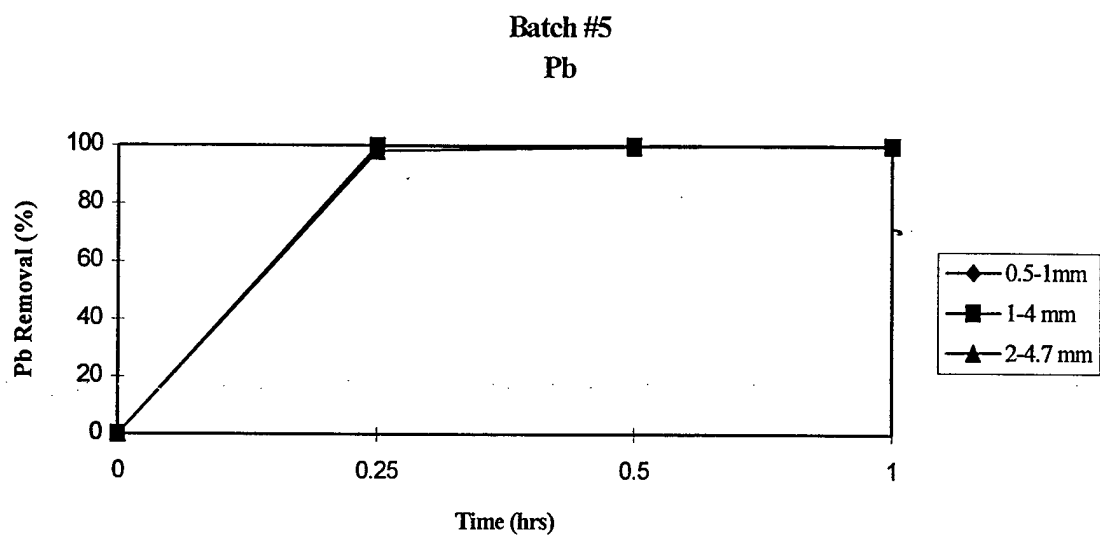


Figure 4.15 Batch Test #5 UW Zeolite Pb Sorption with Time

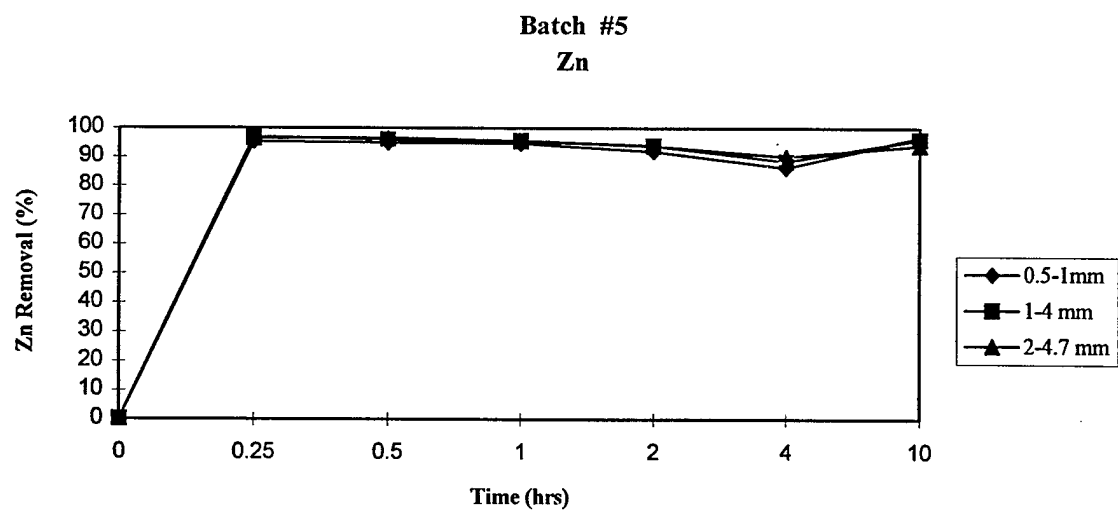


Figure 4.16 Batch Test #5 UW Zeolite Zn Sorption with Time

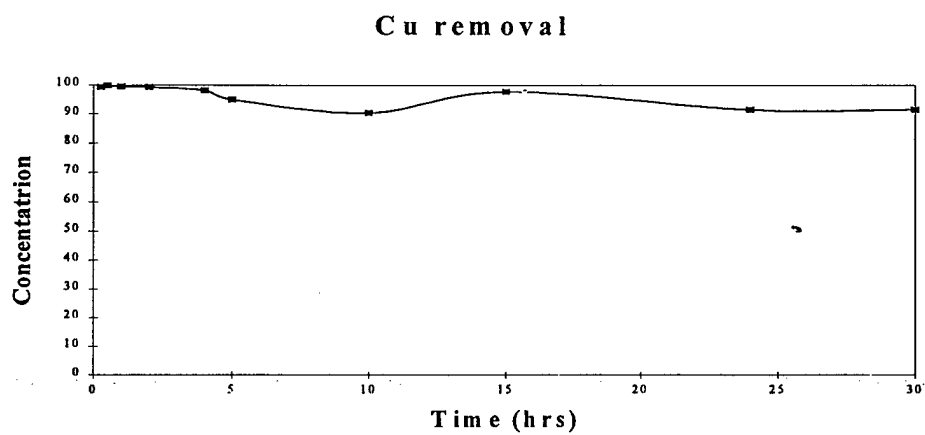


Figure 4.17 Batch Test #5 UW Zeolite Cu sorption with Time

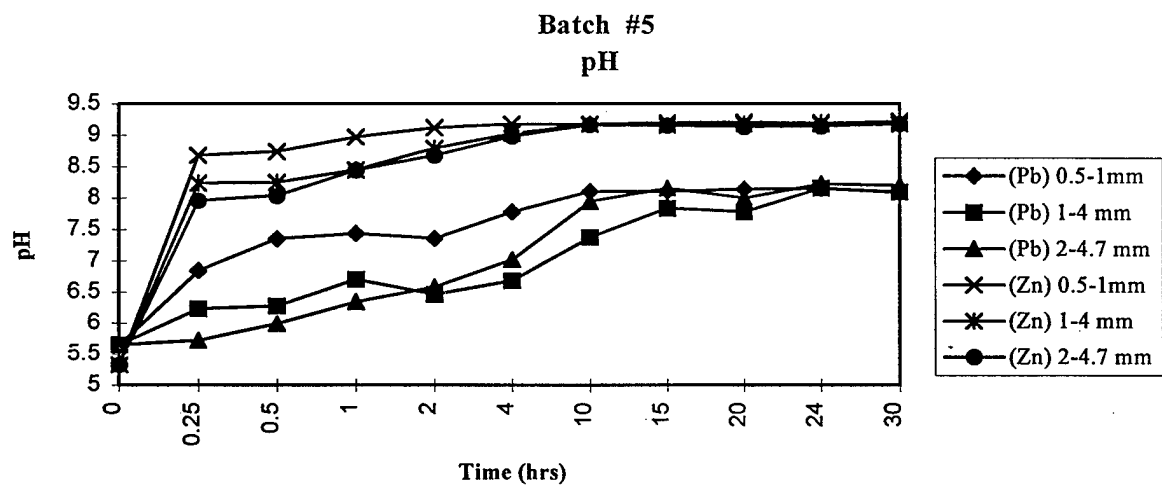


Figure 4.18 Batch test #5 UW Zeolite - PH

Pb, Zn & Cu Sorption with Time

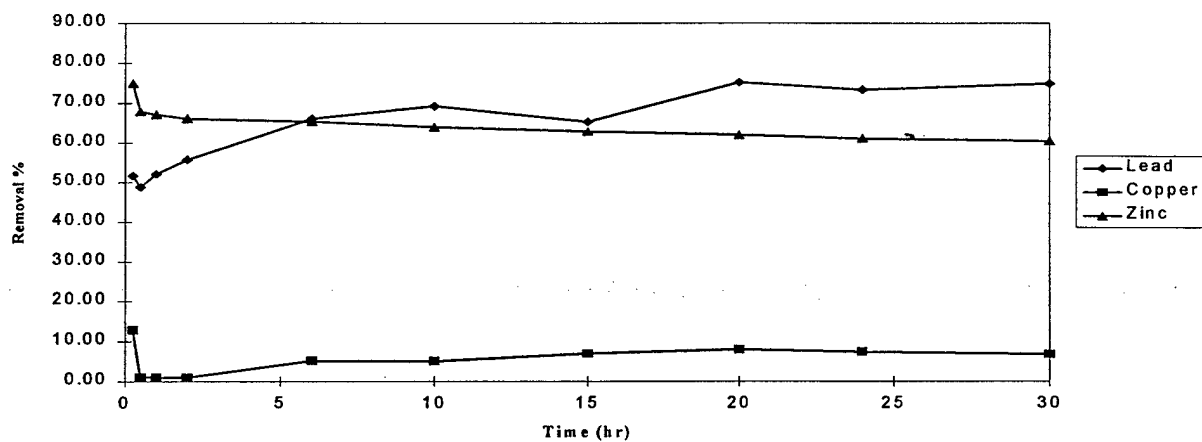


Figure 4.19 Batch Test #4 AW Washed Zeolite (2.0-4.7mm) Pb, Zn & Cu Sorption with Time

pH Change with Time

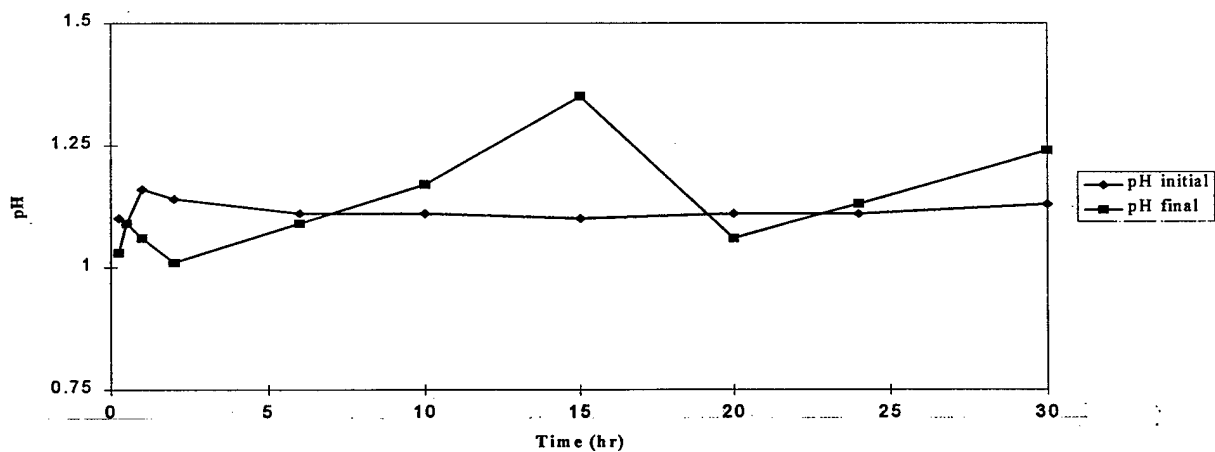


Figure 4.20 Batch Test #4 AW Zeolite (2.0-4.5 mm) pH Change with Time

# UW Zeolite - Pb

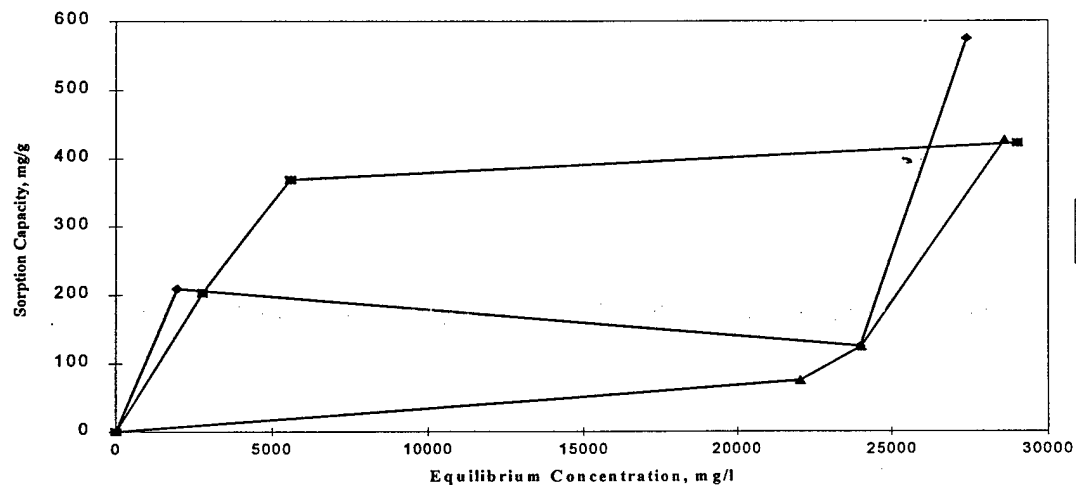


Figure 4.21 Batch Test #1 UW Zeolite - Synthetic Pb Solution

# AW Zeolite - Pb

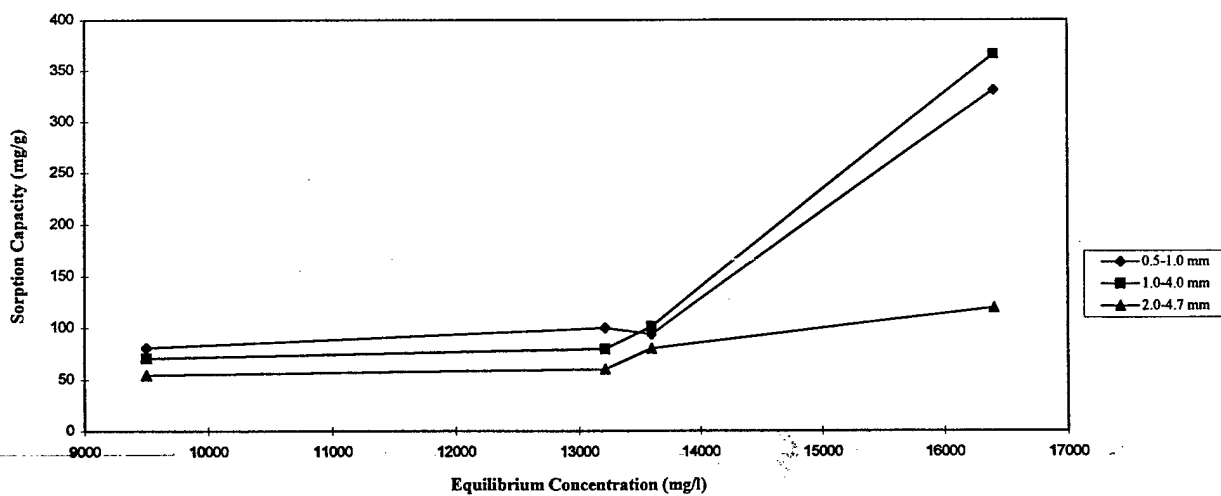


Figure 4.22 Batch Test #2 AW Zeolite - Pb Sorption Isotherms

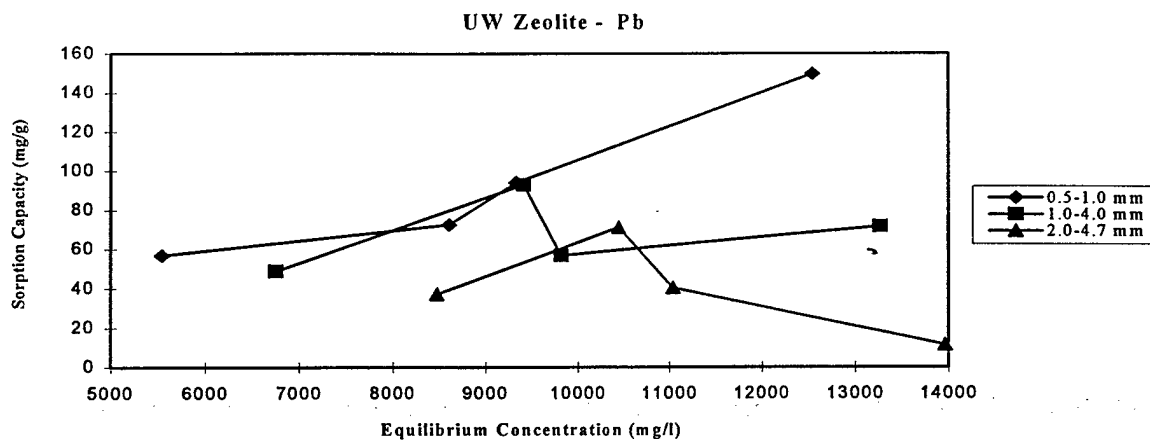


Figure 4.23 Batch Test #2 UW Zeolite - Pb Sorption Isotherms

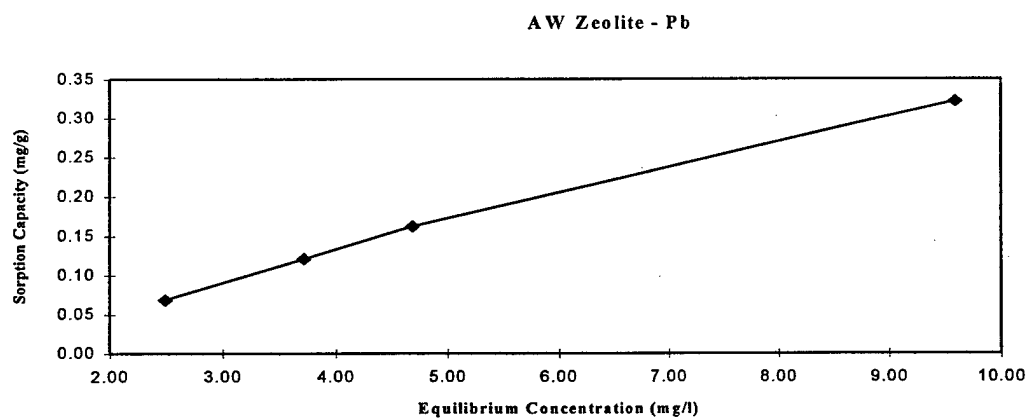


Figure 4.24 Batch Test #3 AW Zeolite - Pb Sorption for Picatinney Extract



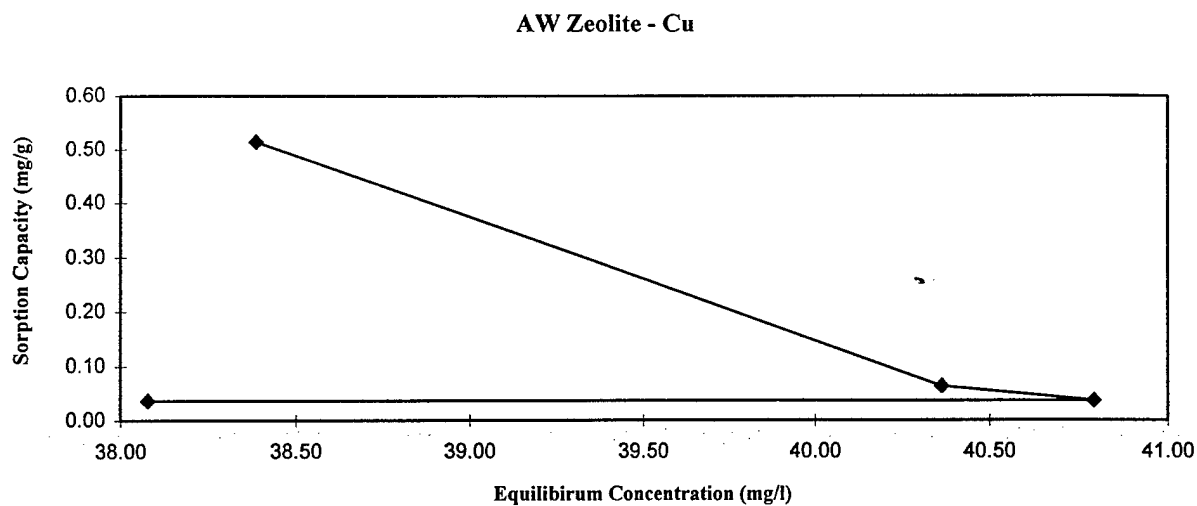


Figure 4.25 Batch Test #3 AW Zeolite - Cu Sorption for Picatinney Extract

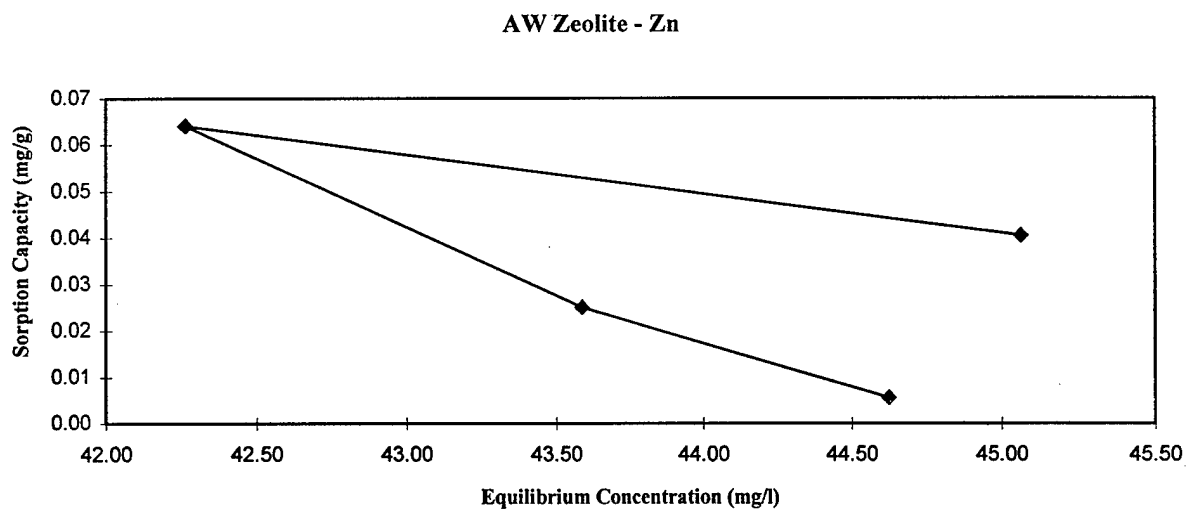


Figure 4.26 Batch Test #3 AW Zeolite - Zn Sorption for Picatinney Extract

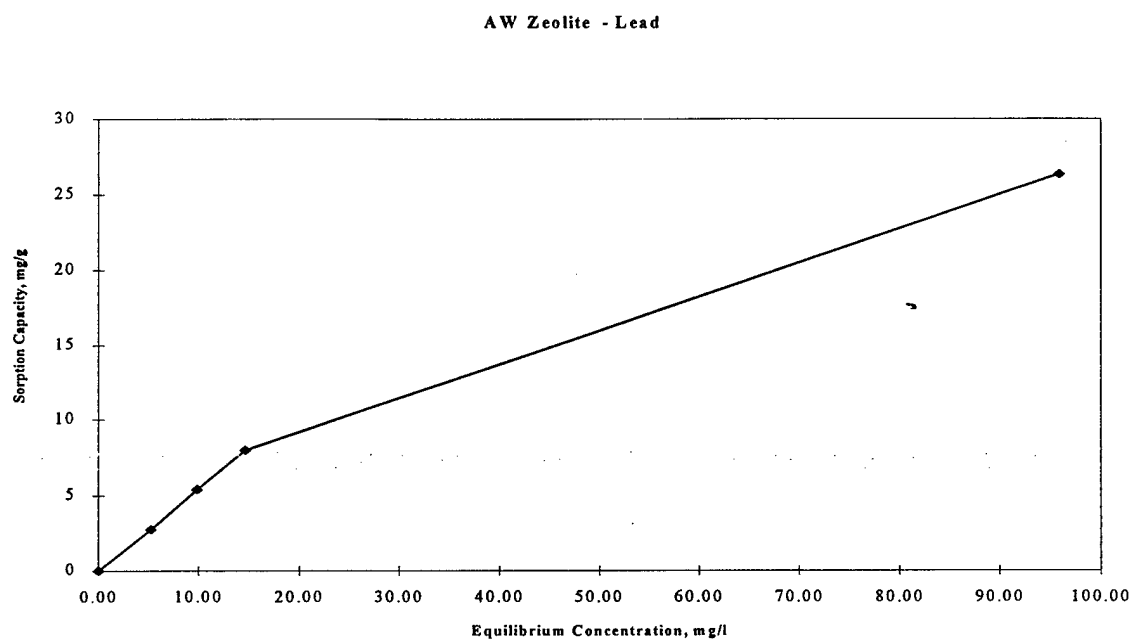


Figure 4.27 Batch Test #8 AW Zeolite - Lead Sorption for FBH Extract

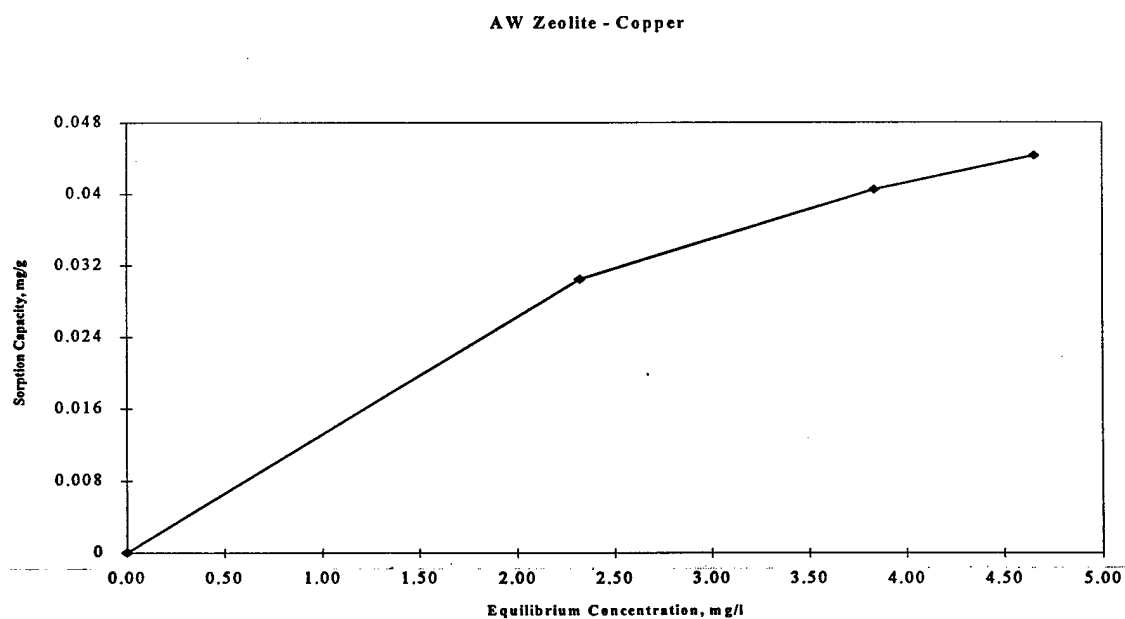


Figure 4.28 Batch Test #8 AW Zeolite - Copper Sorption for FBH Extract

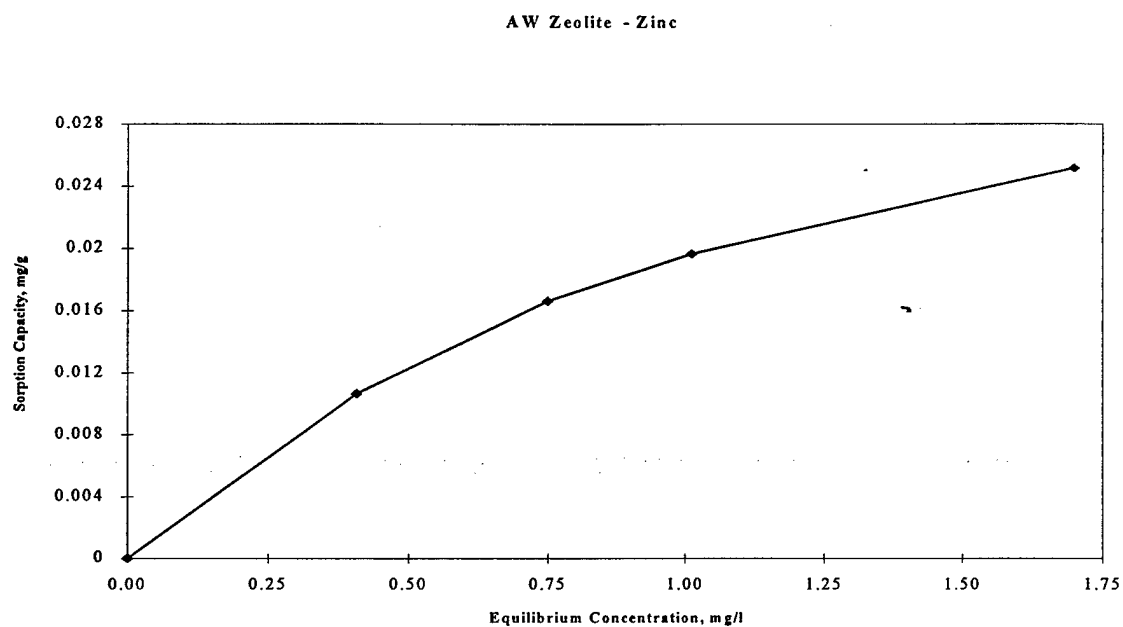


Figure 4.29 Batch Test #8 AW Zeolite - Zinc Sorption for FBH Extract

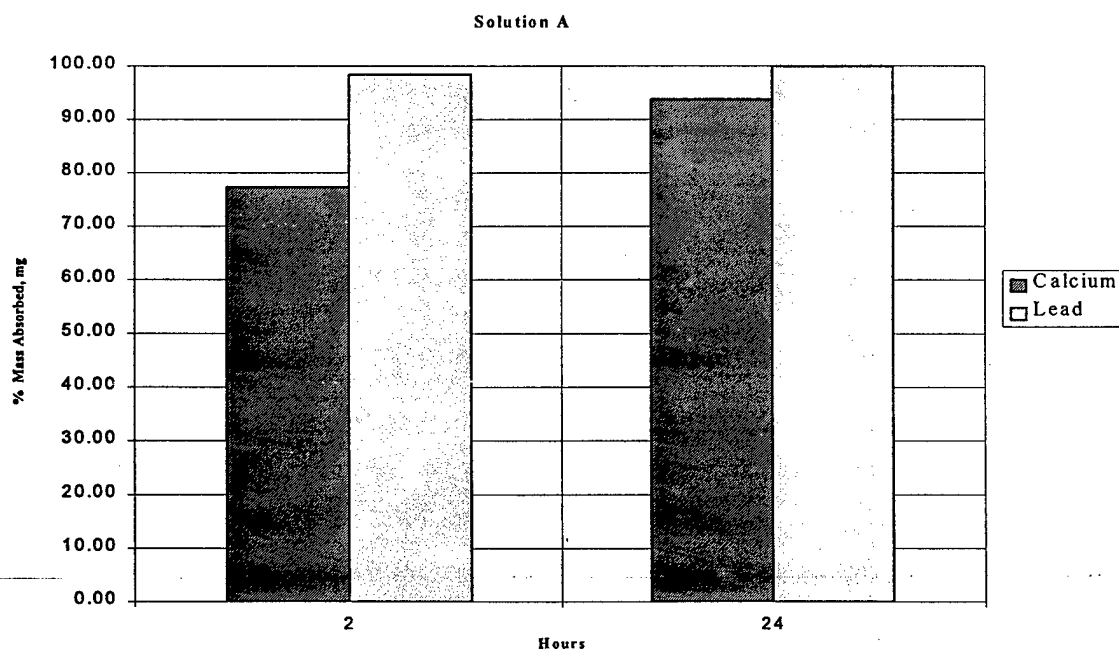


Figure 4.30 Selectivity of Zeolite for Solution A

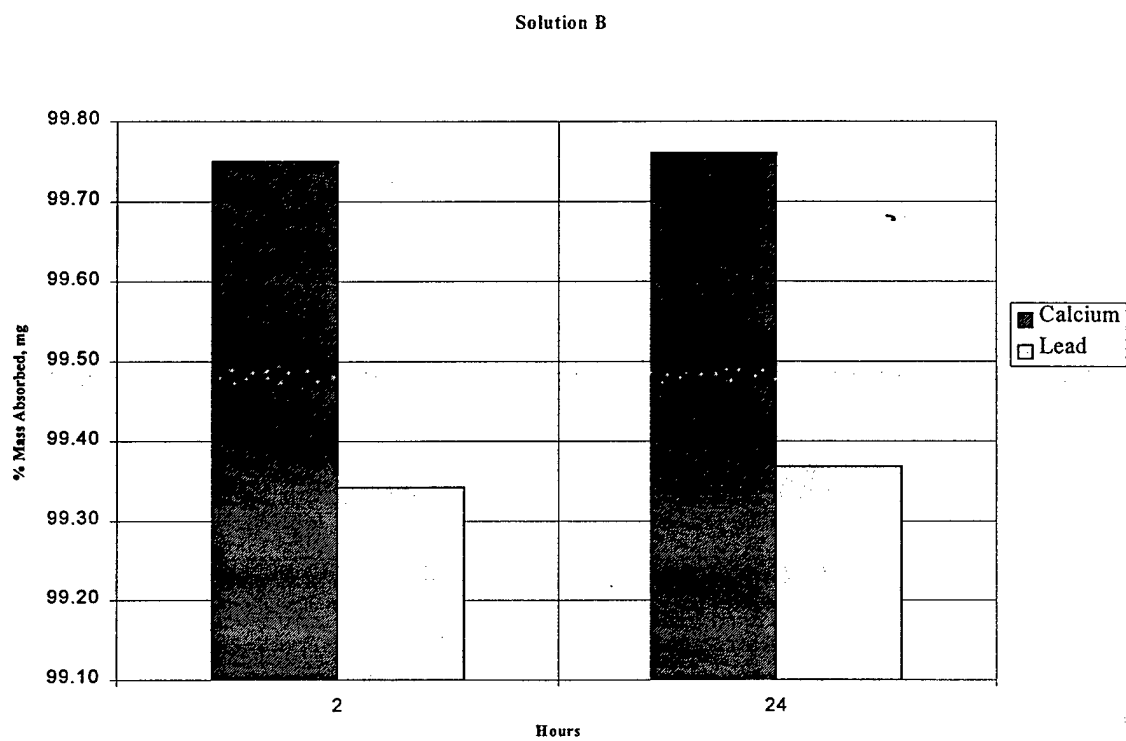


Figure 4.31 Selectivity of Zeolite for Solution B

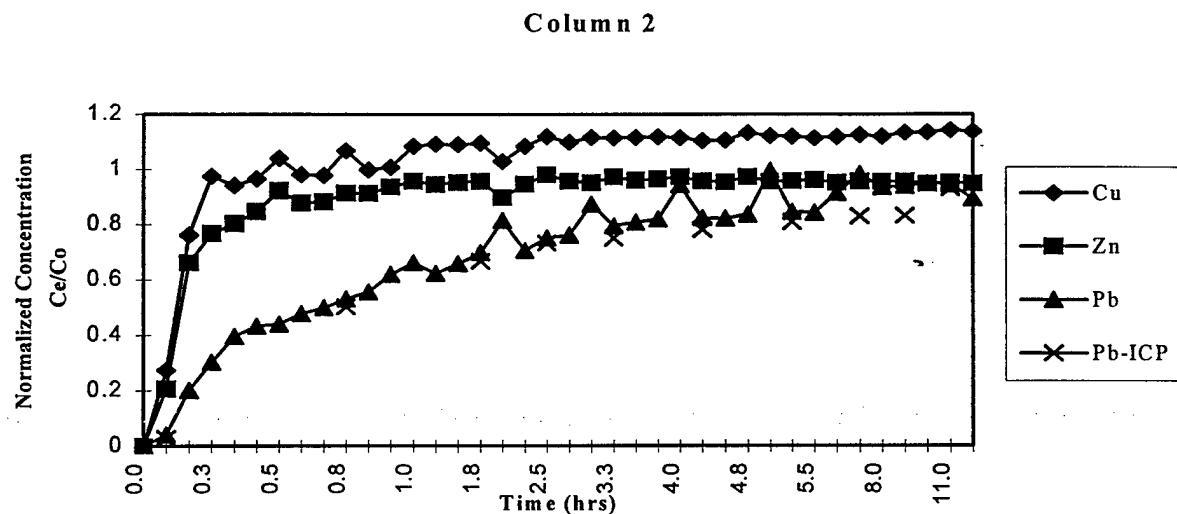


Figure 4.32 Column 2 UW Zeolite 3.0 BV/hr Pb, Zn & Cu Breakthrough Curves

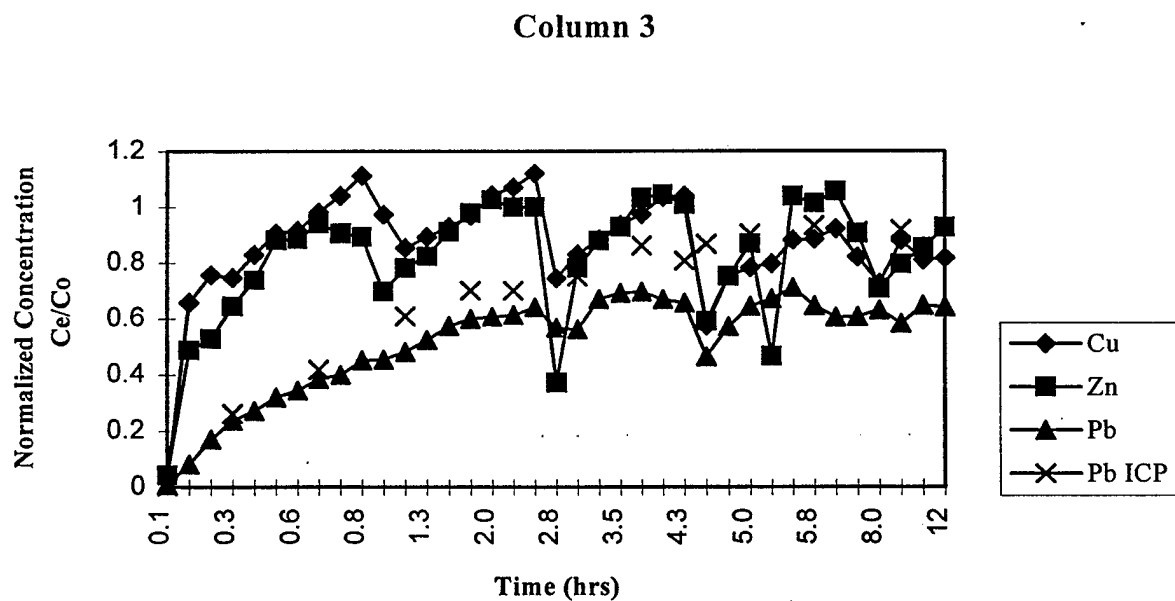


Figure 4.33 Column 3 AW 3.0 BV/hr Pb, Zn & Cu Breakthrough Curves

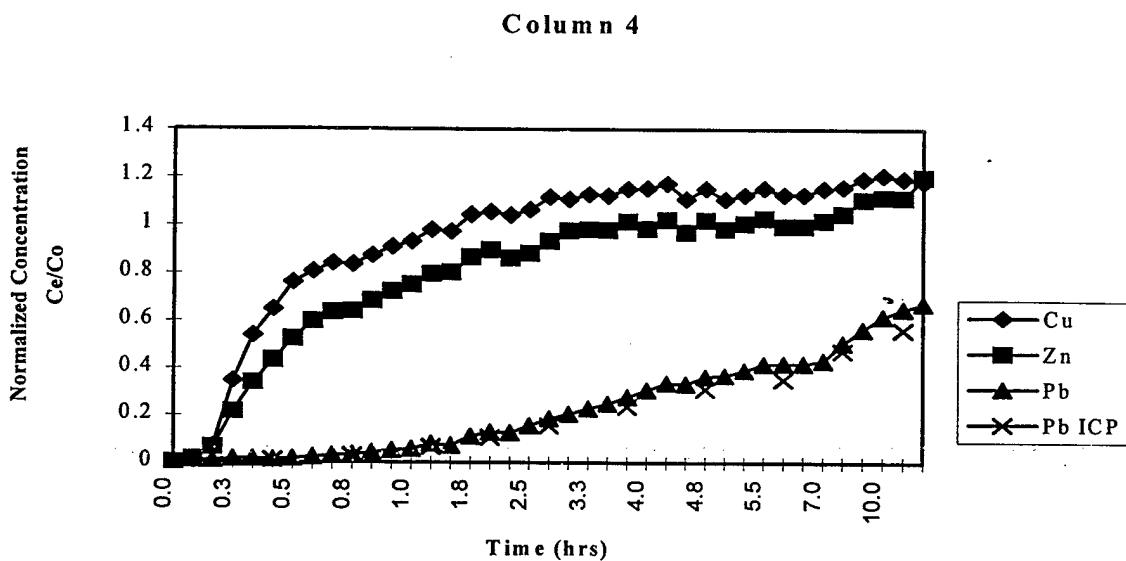


Figure 4.34 Column 4 UW Zeolite 1.0 BC/hr Pb, Zn & Cu Breakthrough Curves

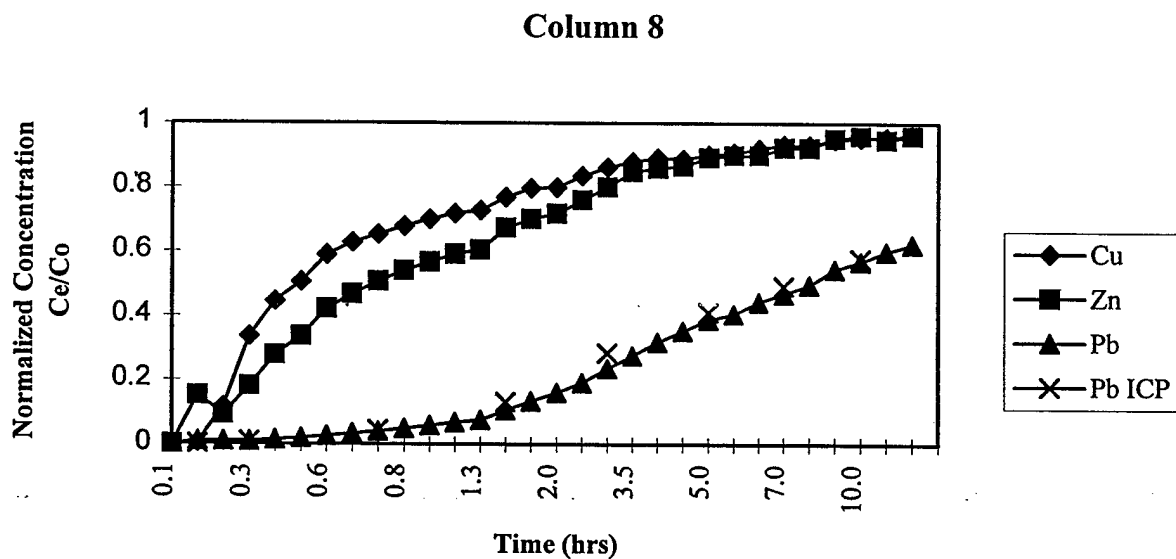


Figure 4.35 Column 8 AW Zeolite 1.0 BV/hr Pb, Zn & Cu Breakthrough Curves

Column 6

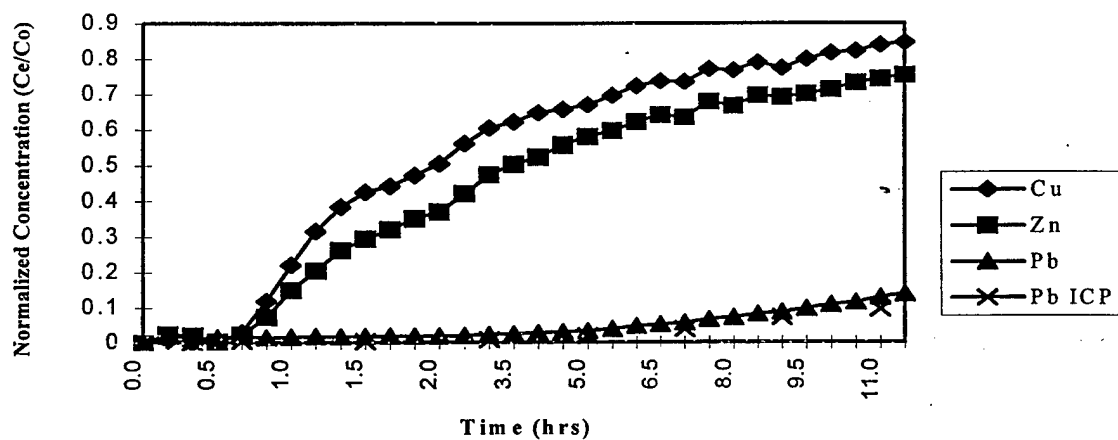


Figure 4.36 Column 6 UW Zeolite 0.3 BV/hr Pb, Zn & Cu Breakthrough Curves

Column 7

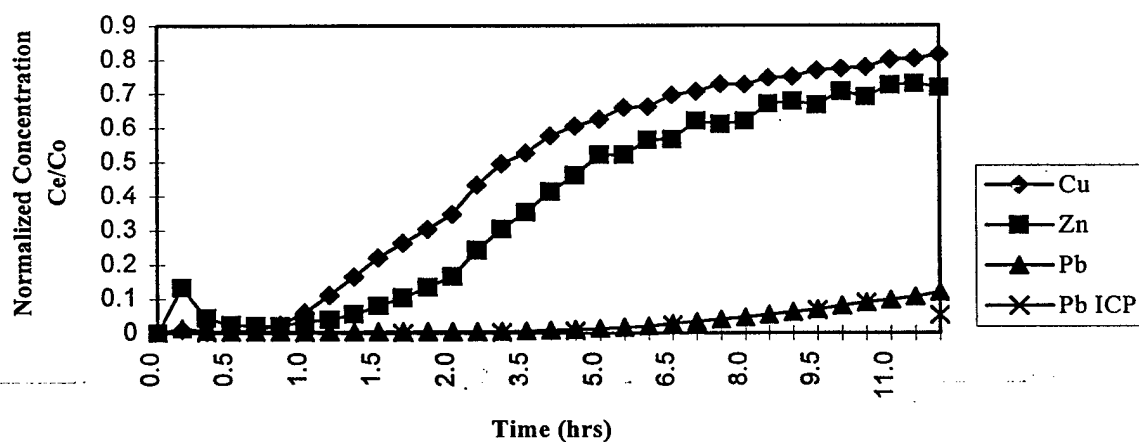


Figure 4.37 Column 7 AW Zeolite 0.3 BV/hr Pb, Zn & Cu Breakthrough Curves

### Column 5

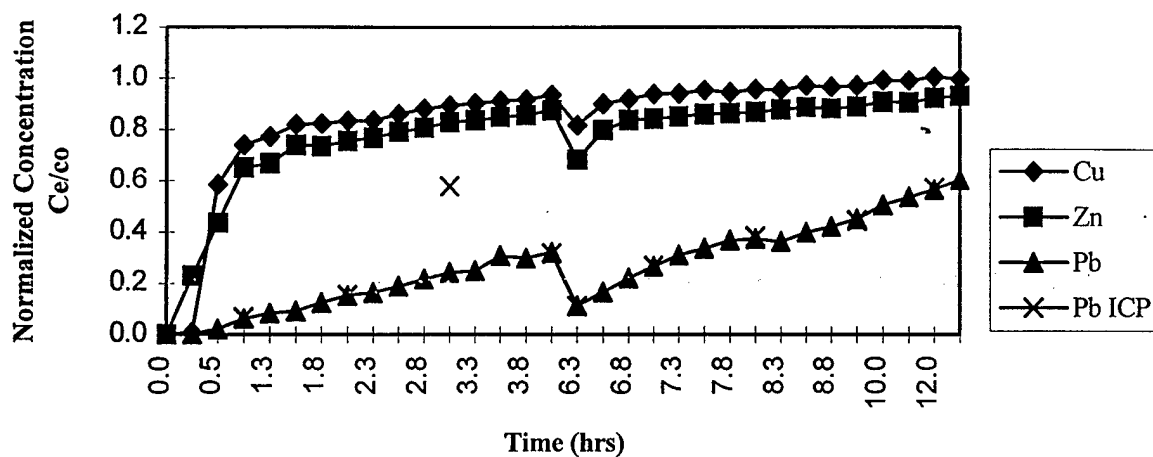


Figure 4.38 Column 5 AW Zeolite - Stop Flow Study Pb, Zn & Cu Breakthrough Curves

### Column 9

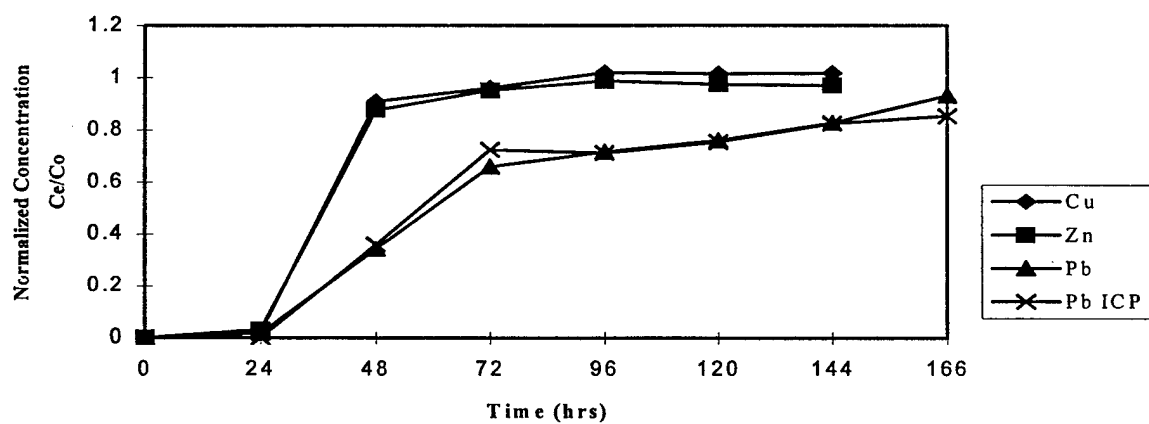


Figure 4.39 Column 9 UW Zeolite - 7 Day Study Pb, Zn & Cu Breakthrough Curves



Column 10

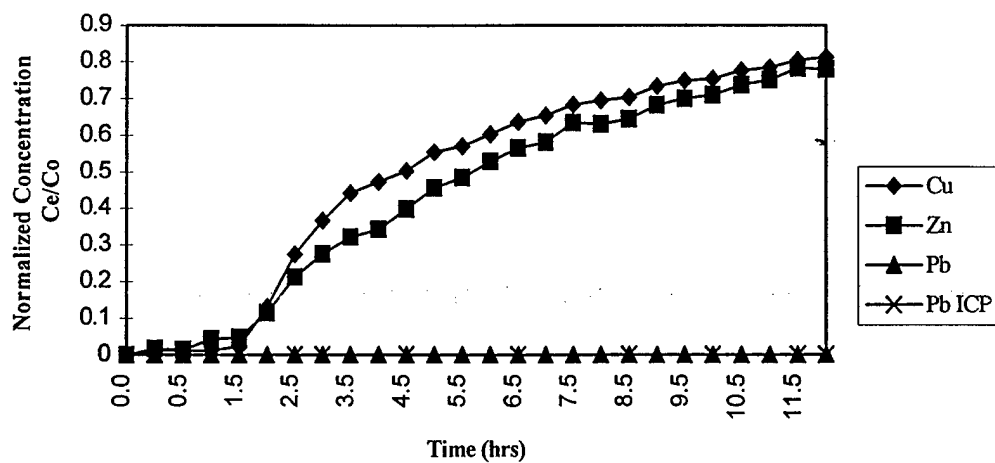


Figure 4.40 Column 10 0.5-1.0 mm UW Zeolite 0.3 BV/hr Pb, Zn & Cu Breakthrough Curves

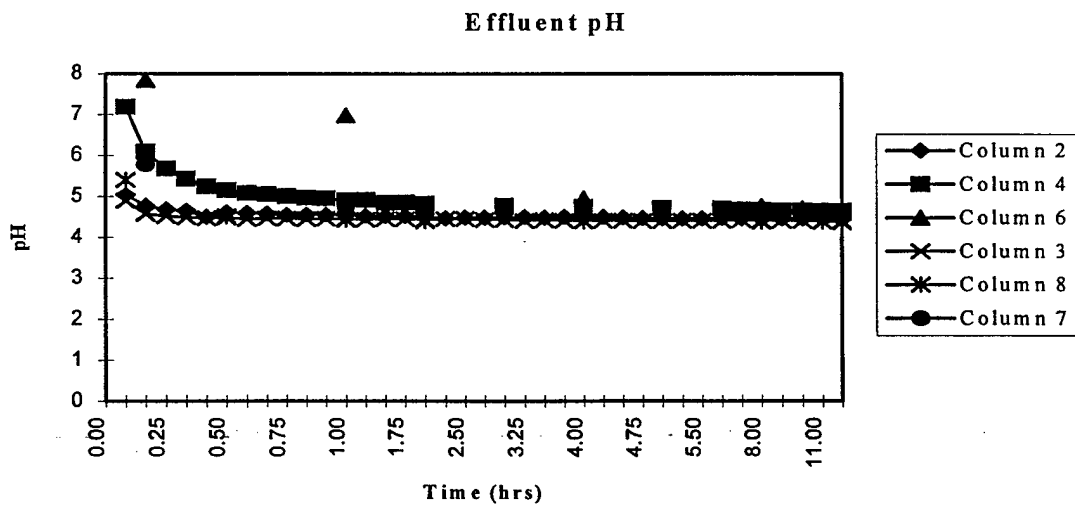


Figure 4.41 Effluent Ph

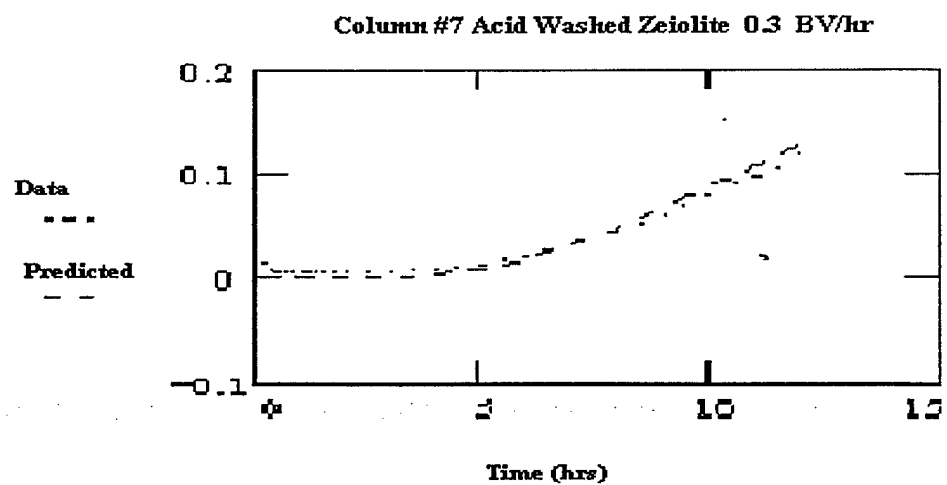


Figure 4.42 Column 7 AW Zeolite 0.3 BV/hr

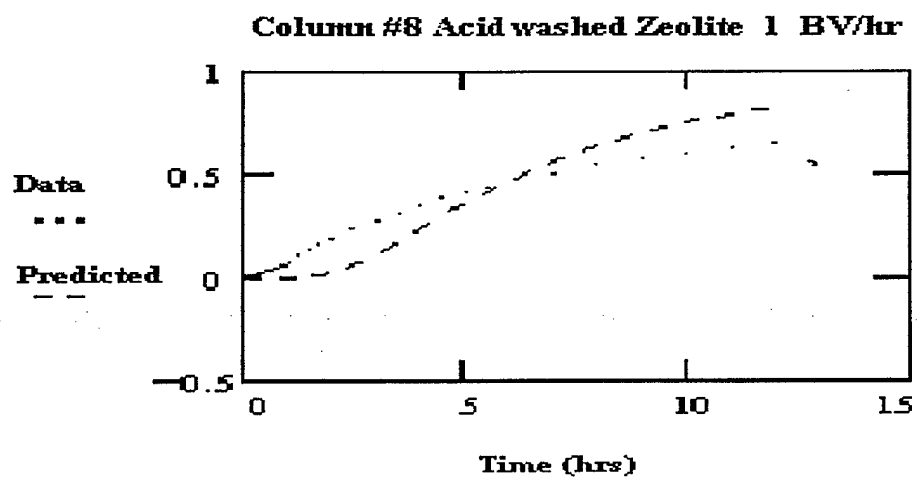


Figure 4.43 Column 8 AW Zeolite 1 BV/hr

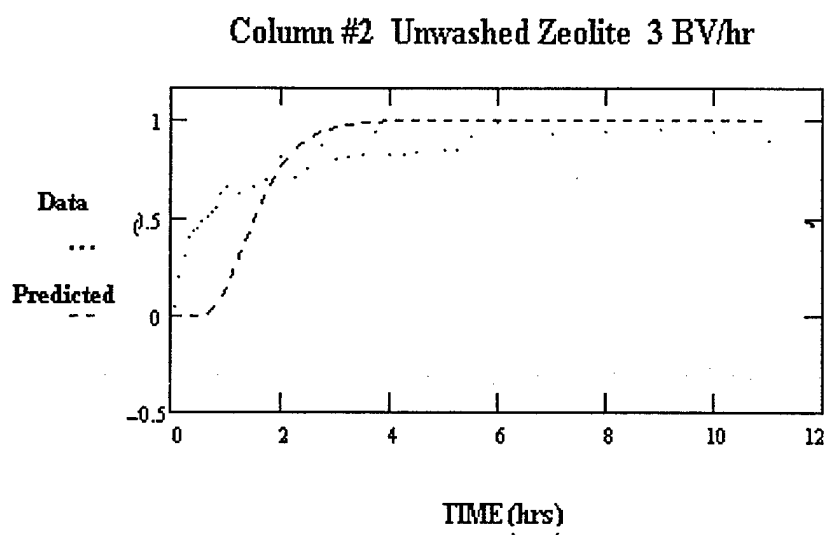


Figure 4.44 Column 2 UW Zeolite 3 BV/hr

## APPENDIX A

### BATCH STUDIES RESULTS

Table A.1: (Batch Test #5 - Pb) Kinetic Study Results  
 Synthetic Solution 1000 mg/L Pb (856 mg/L measured initial concentration)

Time	pH			Percent Removal		
hrs	0.5-1mm	1-4mm	2-4.7mm	0.5-1mm	1.4mm	2-4.7mm
0	5.65	5.65	5.65			
0.25	6.84	6.23	5.72	99.96	99.77	98.07
0.5	7.35	6.27	5.99	99.98	99.84	99.61
1	7.44	6.37	6.34	99.95	99.89	99.82
2	7.36	6.46	6.58	99.95	99.73	99.9
4	7.78	6.68	7.02	99.93	99.83	99.95
10	8.11	7.38	7.95	99.88	99.75	99.91
15	8.11	7.84	8.16	99.87	99.94	99.85
20	8.14	7.78	8.0	99.89	99.78	99.88
24	8.15	8.16	8.23	99.89	99.85	99.91
30	8.09	8.1	8.2	100	99.82	99.89

Table A.2: (Batch Study #5 - Zn) Kinetic Study Results

Synthetic Solution 50.0mg/L Zn (50.7 mg/L measured initial concentration)

Time	pH			Percent Removal		
hrs	0.5-1mm	1-4 mm	2-4.7mm	0.5-1mm	1-4mm	2-4.7mm
0	5.33	5.33	5.33			
1.25	8.68	8.24	7.96	95.27	97.28	96.86
0.5	8.74	8.25	8.04	95.94	96.45	97.0
1	8.97	8.45	8.44	95.74	96.11	96.06
2	9.12	8.79	8.68	93.5	94.5	94.40
4	9.18	9.03	8.98	89.05	89.68	91.20
10	9.17	9.18	9.16	97.46	96.61	94.02
15	9.2	9.15	9.15	97.0	95.44	94.91
20	9.21	9.18	9.13	97.12	94.32	92.70
24	9.18	9.2	9.14	96.09	95.40	93.16
30	9.22	9.17	9.18	95.56	91.42	87.63

Table A.3: (Batch Test #5 - Cu) Kinetic Study Results  
 Synthetic Solution 50.0 mg/L Cu (54.0 mg/L measured initial concentration)

Time	pH			Percent Removal		
hrs	0.5-1mm	1-4mm	2-4.7mm	0.5-1mm	1.4mm	2-4.7mm
0	N/A	N/A	5.33	N/A	N/A	
0.25			7.96			99.35
0.5			8.04			99.72
1			8.44			99.44
2			8.68			99.26
4			8.98			98.15
10			9.16			95.19
15			9.15			90.47
20			9.13			97.68
24			9.14			91.48
30			8.2			99.39



Table A.4: (Batch Test #4) Kinetic Study  
2-4.7 mm Acid Washed Zeolite with Picatinney Extract

Time	pH	pH	Removal (%)		
(hrs)	Initial	Final	Pb	Cu	Zn
0.25	1.10	1.03	51.72	12.83	74.89
0.5	1.09	1.09	48.83	0.00	67.90
1	1.16	1.06	52.11	0.97	67.14
2	1.14	1.01	55.78	0.94	66.08
6	1.11	1.09	66.09	5.20	65.33
10	1.11	1.17	69.22	4.99	63.92
15	1.10	1.35	65.31	6.92	62.90
20	1.11	1.06	75.16	7.93	61.99
24	1.11	1.13	73.28	7.37	61.08
30	1.13	1.24	74.84	6.75	60.42

Table A.5: (Batch Test #1) Equilibrium Batch Study  
 Synthetic Solution Pb 30,000 mg/l  
 Unwashed Zeolite  
 Contact Time 2 hrs

Particle Size	Mass (Approx)	pH		Removal	Capacity
(Mm)	(g)	Initial	Final	(%)	(mg/g)
0.5-1.0	1	2.18	3.13	14.04	426.6
	5	2.23	3.77	30.6	197.79
	7.5	2.32	3.73	27.9	123.8
	15	2.33	3.64	33.8	74.4
1.0-4.0	1	2.15	2.60	17.7	574.7
	5	2.23	3.68	3.30	21.3
	7.5	2.26	3.80	28.0	124.5
	15	2.96	4.48	94.1	209.0
2.0-4.7	1	2.12	2.29	12.8	422.2
	5	2.18	3.66	24.2	156.5
	7.5	2.89	4.35	83.2	368.8
	15	2.92	4.43	91.6	202.9



Table A.7: (Batch Test #3) Equilibrium Batch Study  
Acid Washed Zeolite 2.0-4.7mm with Picatinney Extract

Particle Size	Mass (Approx)	pH		Removal (%)				Capacity (mg/g)		
(Mm)	(g)	Initial	Final	Pb	Zn	Cu	Pb	Zn	Cu	
2.0-4.7	1	1.19	1.24	25.0	0.89	11.7	0.32	0.04	0.51	
	5	1.17	1.20	63.4	7.1	7.4	0.16	0.064	0.063	
	7.5	1.13	1.17	70.9	4.2	6.2	0.12	0.025	0.037	
	15	1.12	1.17	80.5	1.7	12.6	0.07	0.0057	0.036	

Table A.8: (Batch Test #7) Equilibrium Study  
FBH Extract

24 hr Contact Time				
Particle Size	Initial Conc	Mass (Approx)	Removal (%)	Capacity (mg/g)
(mm)	(mg/l)	(g)		
2.0-4.7	Pb: 421	1	77.2	26.3
		5	96.4	8.0
		7.5	97.6	5.4
		15	98.8	2.8
	Zn: 2.01	1	15.5	0.025
		5	49.7	0.020
		7.5	62.7	0.0166
		15	79.7	0.011
	Cu: 6.91	1	7.4	0.0414
		5	32.6	0.0443
		7.5	44.5	0.0405
		7.15	66.4	0.0305

Table A.9: (Batch Test #6) Selectivity Test			
Initial Concentration	Contact Time	Removal (%)	
mg/l	hrs	Pb	Ca
500 Pb/100 Ca	2	98.43	77.30
	24	99.91	93.80
50 Pb/100 Ca	2	99.34	99.75
	24	99.37	99.76

## APPENDIX B

### DATA

## SCREENING STUDIES



Bark - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	19950	5.0082	3.67	3.22	21300	-26.96	-6.77
Pb b	9320	5.0056	3.91	3.47	5935	67.62	36.32
Pb c	4925	5.0031	3.98	4.16	1960	59.26	60.20
Pb d	483	5.0012	4.26	4.31	21	9.24	95.65
Pb e	48.63	5.0069	4.16	4.29	0.82	0.95	98.31
Hg a	3003	5.00129	4.10	3.98	1238	35.29	58.77
Hg b	16879	5.00052	3.45	3.53	10507	127.43	37.75
Hg c	7809	4.99875	4.21	3.85	3848	79.24	50.72
Hg d	726.9	5.00040	3.80	3.92	42.4	13.69	94.17
Hg e	54.7	5.00170	4.10	3.54	4.3	1.01	92.14
Cd a	20020	5.0041	3.90	3.82	18900	22.38	5.59
Cd b	9320	5.0011	3.84	3.90	10300	-19.60	-10.52
Cd c	4690	5.0019	4.10	4.22	3940	14.99	15.99
Cd d	418	4.9987	4.08	4.56	223	3.90	46.65
Cd e	47.2	4.9996	4.37	4.58	9.9	0.75	79.03
Cr a	10020	4.9997	4.29	2.76	11420	-28.00	-13.97
Cr b	4760	5.0013	4.22	2.74	4390	7.40	7.77
Cr c	2310	5.0024	4.24	2.94	2015	5.90	12.77
Cr d	262	5.0005	4.07	4.59	55	4.14	79.01
Cr e	24.49	5.0026	4.33	4.93	7.95	0.33	67.54

Activated Carbon - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	19950	5.0011	3.43	3.85	12810	142.77	35.79
Pb b	9320	5.0070	3.80	4.26	5010	86.08	46.24
Pb c	4925	5.0017	3.78	4.88	1443	69.62	70.70
Pb d	483	5.0050	4.36	5.65	4.5	9.56	99.07
Pb e	48.63	5.0025	4.20	5.52	0.07	0.97	99.86
Hg a	3003	4.99860	4.22	4.92	67	58.74	97.77
Hg b	14704	4.99961	3.92	4.40	838	277.34	94.30
Hg c	7697	5.00320	4.04	4.65	193	149.98	97.49
Hg d	716	4.99843	4.04	4.52	3.1	14.26	99.57
Hg e	61.7	5.00223	4.33	5.25	0	1.23	100.00
Cd a	20020	5.0004	3.49	4.99	18600	28.40	7.09
Cd b	9320	5.0036	4.03	5.24	8200	22.38	12.02
Cd c	4690	5.0040	4.24	5.35	3740	18.98	20.26
Cd d	418	4.9979	4.18	5.80	212	4.12	49.28
Cd e	47.2	5.0006	4.43	5.69	7.3	0.80	84.53
Cr a	10020	4.9985	4.00	3.37	10140	-2.40	-1.20
Cr b	4760	5.0008	4.16	3.07	4450	6.20	6.51
Cr c	2310	4.9987	4.08	3.93	1775	10.70	23.16
Cr d	262	5.0035	4.35	5.95	17	4.90	93.51
Cr e	24.49	4.9996	4.42	5.93	0.57	0.48	97.67

Corn Cob - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	18420	5.0036	3.63	3.63	17758	13.23	3.59
Pb b	9294	4.9992	3.97	4.10	8571	14.46	7.78
Pb c	4539	5.0046	4.18	4.41	3620	18.36	20.25
Pb d	440.1	5.0001	4.30	5.03	163.8	5.53	62.78
Pb e	43.33	5.0009	4.26	5.05	15.26	0.56	64.78
Hg a	3003	4.99860	4.17	4.20	2368	12.70	21.15
Hg b	14704	5.00413	4.09	4.24	14975	-5.42	-1.84
Hg c	7697	5.00350	4.16	4.17	6579	22.34	14.53
Hg d	716	4.00340	4.19	4.17	429	7.17	40.08
Hg e	61.7	5.00370	4.19	4.23	7.9	1.08	87.20
Cd a	17504	5.0030	3.84	3.71	22612	-102.10	-29.18
Cd b	9111	5.0028	4.01	3.92	9212	-2.02	-1.11
Cd c	4310	5.0023	4.22	4.15	4190	2.40	2.78
Cd d	437.8	5.0009	4.30	4.55	334	2.08	23.71
Cd e	40	5.0020	4.21	4.68	23	0.34	42.50
Cr a	8859	5.0022	4.04	2.55	8477	7.64	4.31
Cr b	4037	5.0037	4.33	2.83	4188	-3.02	-3.74
Cr c	1987	5.0020	4.32	2.97	1901	1.72	4.33
Cr d	197	4.9992	4.30	4.47	122	1.50	38.07
Cr e	21.82	4.9999	4.20	4.72	13.59	0.16	37.72

Cellulose Xanthate - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	19950	5.0075	4.57	4.28	9410	210.48	52.83
Pb b	9320	5.0060	4.22	4.09	3625	113.76	61.11
Pb c	4925	5.0094	4.30	4.57	513	88.07	89.58
Pb d	483.0	5.0088	4.15	4.46	0	9.64	100.00
Pb e	48.63	5.0078	4.24	4.50	0	0.97	100.00
Hg a	3003	4.99815	4.41	4.44	518	49.72	82.75
Hg b	16879	4.99842	4.74	4.46	4035	256.96	76.09
Hg c	7809	5.00734	4.57	4.42	0	155.95	100.00
Hg d	726.9	5.00770	3.52	4.28	36	13.80	95.05
Hg e	54.7	5.00319	4.28	4.37	3.2	1.03	94.15
Cd a	20020	5.0039	4.54	4.54	14720	105.92	26.47
Cd b	9320	5.0016	4.31	4.70	5770	70.98	38.09
Cd c	4690	5.0029	4.30	4.40	2330	47.17	50.32
Cd d	418	5.0034	4.19	4.83	1	8.33	99.76
Cd e	47.2	4.9993	4.34	4.81	0.4	0.94	99.15
Cr a	10020	5.0063	4.11	3.19	10960	-18.78	-9.38
Cr b	4760	5.0022	4.39	3.56	3630	22.59	23.74
Cr c	2310	5.0083	4.42	4.42	1375	18.67	40.48
Cr d	262	5.0039	4.14	4.85	60	4.04	77.10
Cr e	24.49	5.0056	4.31	4.56	8.66	0.32	64.64

Insoluble Starch Xanthate - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	18420	5.0047	4.70	4.74	4863	73.60	270.89
Pb b	9294	5.0000	4.47	4.82	42	99.55	185.04
Pb c	4539	4.9999	4.29	4.61	20	99.56	90.38
Pb d	440.1	5.0038	4.26	4.32	0	100.00	8.80
Pb e	43.33	5.0024	4.13	4.73	0.11	99.75	0.86
Hg a	3003	4.99970	4.43	4.38	33	98.90	59.40
Hg b	14704	4.99925	4.26	4.41	7973	45.78	134.64
Hg c	7697	5.00072	4.26	4.44	907	88.22	135.78
Hg d	716	4.99712	4.62	4.65	319.6	55.36	7.93
Hg e	61.7	4.99725	4.60	4.69	0.4	99.35	1.23
Cd a	17504	5.0000	4.27	4.63	14994	14.34	50.20
Cd b	9111	5.0004	4.22	4.66	5784	36.52	66.53
Cd c	4310	5.0011	4.28	4.77	8	99.81	86.02
Cd d	437.8	5.0012	4.26	4.44	1766	-303.38	-26.56
Cd e	40	4.9999	4.22	4.64	0.7	98.25	0.79
Cr a	8859	4.9998	4.21	2.96	8815	0.50	0.88
Cr b	4037	4.9995	4.22	3.59	3710	8.10	6.54
Cr c	1987	5.0014	4.56	4.43	1042	47.56	18.89
Cr d	197	5.0012	4.27	4.50	176	10.66	0.42
Cr e	21.82	5.0009	4.22	4.91	13.71	37.17	0.16

Kaolinite - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	19950	5.0017	3.31	2.97	18680	25.39	6.37
Pb b	9320	5.0005	3.72	3.35	9055	5.30	2.84
Pb c	4925	5.0009	3.63	3.92	4773	3.04	3.09
Pb d	483.0	5.0044	4.21	4.26	432.5	1.01	10.46
Pb e	48.63	5.0010	4.11	4.22	36.69	0.24	24.55
Hg a	3003	5.00485	4.11	4.22	3006	-0.06	-0.10
Hg b	14704	4.99985	4.01	4.24	15232	-10.56	-3.59
Hg c	7697	4.99930	4.03	4.29	8057	-7.20	-4.68
Hg d	716	4.99813	4.14	4.17	719.8	-0.08	-0.53
Hg e	61.7	5.00070	4.12	4.19	58.3	0.07	5.51
Cd a	20020	5.0014	3.64	3.55	20320	-6.00	-1.50
Cd b	9320	5.0052	3.72	4.05	10840	-30.37	-16.31
Cd c	4690	5.0028	4.09	4.19	4785	-1.90	-2.03
Cd d	418	5.0019	4.06	4.43	458	-0.80	-9.57
Cd e	47.2	5.0090	4.26	4.41	37.4	0.20	20.76
Cr a	10020	5.0050	4.13	3.02	9020	19.98	9.98
Cr b	4760	5.0084	4.26	2.86	5130	-7.39	-7.77
Cr c	2310	5.0036	4.16	2.87	2410	-2.00	-4.33
Cr d	262	5.0082	4.11	4.59	213	0.98	18.70
Cr e	24.49	5.0088	4.29	4.82	13.66	0.22	44.22

Montmorillonite - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	17900	5.00142	3.68	3.65	15500	47.99	13.41
Pb b	8950	5.00685	4.00	3.87	7050	37.95	21.23
Pb c	4375	5.00091	4.34	4.15	3050	26.50	30.29
Pb d	395	5.00729	4.39	4.38	107.5	5.74	72.78
Pb e	47.2	5.00576	4.34	4.51	8.9	0.77	81.14
Hg a	3003	5.00020	4.06	4.09	2874	2.58	4.30
Hg b	14704	5.00295	3.92	4.13	15971	-25.33	-8.62
Hg c	7697	5.00205	3.98	4.12	7616	1.62	1.05
Hg d	716	4.99758	4.09	4.04	721.4	-0.11	-0.75
Hg e	61.7	5.00149	4.07	4.04	58.3	0.07	5.51
Cd a	16920	5.0018	4.46	4.39	14360	51.18	15.13
Cd b	10350	5.0085	4.39	4.40	8680	33.34	16.14
Cd c	5050	5.0007	4.43	4.36	4265	15.70	15.54
Cd d	483	5.0019	4.42	4.36	196	5.74	59.42
Cd e	48.6	5.0082	4.32	4.34	11.9	0.73	75.51
Cr a	9580	5.00693	4.28	2.67	8810	15.38	8.04
Cr b	4730	5.0023	4.35	2.80	4180	10.99	11.63
Cr c	2400	5.0040	4.48	2.98	1960	8.79	18.33
Cr d	232	5.0084	5.02	3.77	22.5	4.18	90.30
Cr e	24.22	5.0005	4.94	4.33	0.29	0.48	98.80

Peat Moss - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	17900	5.0032	4.04	3.48	12300	111.93	31.28
Pb b	8950	5.0028	4.45	3.62	3850	101.94	56.98
Pb c	4375	5.0018	4.53	3.97	775	71.97	82.29
Pb d	395	5.0035	4.53	4.34	0	7.89	100.00
Pb e	47.2	5.0000	4.69	4.52	0.1	0.94	99.79
Hg a	3003	5.00135	4.14	4.68	1737	25.31	42.16
Hg b	16879	5.00645	3.67	3.41	12077	95.92	28.45
Hg c	7809	4.99980	3.78	3.50	5173	52.72	33.76
Hg d	726.9	5.00610	5.00	3.32	80.5	12.91	88.93
Hg e	54.7	4.99974	4.00	4.14	0	1.09	100.00
Cd a	16920	5.0002	4.23	3.88	13200	74.40	21.99
Cd b	10350	5.0081	4.23	4.02	6670	73.48	35.56
Cd c	5050	5.0076	4.41	4.09	2860	43.73	43.37
Cd d	483	5.0069	4.30	4.23	23	9.19	95.24
Cd e	48.6	5.0083	4.13	4.31	1.7	0.94	96.50
Cr a	9580	5.0036	4.27	2.67	7820	35.17	18.37
Cr b	4730	5.0030	4.31	2.72	3700	20.59	21.78
Cr c	2400	5.0084	4.52	2.87	1610	15.77	32.92
Cr d	232	5.00338	4.75	3.49	3	4.58	98.71
Cr e	24.22	5.00909	4.84	4.03	0.13	0.48	99.46



Seaweed #2 - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	17900	5.00433	4.04	3.98	5800	241.79	67.60
Pb b	8950	5.0009	4.45	4.46	1000	158.97	88.83
Pb c	4375	5.0007	4.53	4.69	100	85.49	97.71
Pb d	395	5.00453	4.53	5.08	13	7.63	96.71
Pb e	47.2	5.00574	4.69	5.70	1	0.92	97.88
Hg a	3003	5.00506	4.32	4.68	520	49.61	82.68
Hg b	16879	5.00561	3.80	3.85	8004	177.30	52.58
Hg c	7809	4.99757	4.27	4.18	2639	103.45	66.21
Hg d	726.9	5.00512	4.74	5.17	7.1	14.38	99.02
Hg e	54.7	5.00194	4.04	4.85	0.9	1.08	98.35
Cd a	16920	5.00533	4.40	4.51	13380	70.72	20.92
Cd b	10350	5.0074	4.42	4.79	5050	105.84	51.21
Cd c	5050	5.00797	4.62	4.90	2175	57.41	56.93
Cd d	483	5.00188	4.73	5.20	118	7.30	75.57
Cd e	48.6	5.0005	4.88	5.65	12.8	0.72	73.66
Cr a	9580	5.00321	4.30	2.69	6620	59.16	30.90
Cr b	4730	5.0026	4.38	2.86	2840	37.78	39.96
Cr c	2400	5.00099	4.76	3.36	645	35.09	73.13
Cr d	232	5.00358	4.79	4.63	150	1.64	35.34
Cr e	24.22	5.00092	4.86	4.88	14.07	0.20	41.91

Zeolite - Single Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Pb a	18420	5.0023	4.43	4.85	0	368.23	100.00
Pb b	9294	5.0027	4.64	5.13	0	185.78	100.00
Pb c	4539	5.0002	4.83	5.36	0	90.78	100.00
Pb d	440.1	5.0028	4.59	5.18	0	8.80	100.00
Pb e	43.33	5.0021	4.71	5.72	0	0.87	100.00
Hg a	3003.0	5.00733	4.39	5.00	2925.0	1.56	2.60
Hg b	16879.0	4.99770	4.86	5.16	16853.0	0.52	0.15
Hg c	7809.0	5.00725	4.45	4.91	8130.0	-6.41	-4.11
Hg d	726.9	4.99991	4.10	4.81	596.4	2.61	17.95
Hg e	54.7	4.99762	4.70	4.98	20.6	0.68	62.34
Cd a	17504.0	5.00310	4.52	4.79	7786.0	194.24	55.52
Cd b	9111.0	5.00998	4.65	5.08	938.0	163.13	89.70
Cd c	4310.0	5.00042	4.78	5.15	144.0	83.31	96.66
Cd d	40.0	5.00700	4.48	6.08	2.0	0.76	95.00
Cd e	437.8	5.00850	4.30	6.11	0.4	8.73	99.91
Cr a	8859.00	5.00215	4.32	4.27	4832	80.51	45.46
Cr b	4037.00	5.00121	4.28	4.39	1714	46.45	57.54
Cr c	1987.00	5.00377	4.72	5.22	24	39.23	98.79
Cr d	197.00	5.00799	4.87	5.43	0	3.93	100.00
Cr e	21.82	5.00350	4.54	5.15	0	0.44	100.00

Bark - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	5.0034	3.56	2.88	2120	26.78	38.73
Hg	2425				1075	26.98	55.67
Cd	2244				2102	2.84	6.33
Cr	721				569	3.04	21.08
Multi b							
Pb	1880.0	4.9998	3.83	3.26	780	22.00	58.51
Hg	1153.0				328	16.50	71.55
Cd	1230.0				1040	3.80	15.45
Cr	360.8				189	3.44	47.62
Multi c							
Pb	825.0	4.9984	3.99	3.68	150.0	13.50	81.82
Hg	374.0				74.0	6.00	80.21
Cd	537.0				449.0	1.76	16.39
Cr	124.7				64.5	1.20	48.28
Multi d							
Pb	163.00	5.0012	4.23	4.21	4.00	3.18	97.55
Hg	104.60				0.60	2.08	99.43
Cd	122.60				45.10	1.55	63.21
Cr	31.64				10.01	0.43	68.36
Multi e							
Pb	16.60	5.0013	4.33	4.32	0.10	0.33	99.40
Hg	6.60				0.00	0.13	100.00
Cd	10.74				1.94	0.18	81.94
Cr	3.43				1.01	0.05	70.55

Carbon - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	5.0047	3.89	3.64	1940	30.37	43.93
Hg	2425				90	46.66	96.29
Cd	2244				2140	2.08	4.63
Cr	721				356	7.29	50.62
Multi b							
Pb	1880.0	5.0004	4.10	4.42	400.0	29.60	78.72
Hg	1153.0				33.0	22.40	97.14
Cd	1230.0				1073.0	3.14	12.76
Cr	360.8				106.5	5.09	70.48
Multi c							
Pb	825.0	5.0052	4.36	5.14	30.0	15.88	96.36
Hg	374.0				3.0	7.41	99.20
Cd	537.0				366.0	3.42	31.84
Cr	124.7				11.7	2.26	90.62
Multi d							
Pb	163.00	5.0008	3.88	4.31	5.00	3.16	96.93
Hg	104.60				1.80	2.06	98.28
Cd	122.60				76.10	0.93	37.93
Cr	31.64				4.83	0.54	84.73
Multi e							
Pb	16.60	5.0056	4.06	4.57	0.10	0.33	99.40
Hg	6.60				0.00	0.13	100.00
Cd	10.74				2.74	0.16	74.49
Cr	3.43				0.16	0.07	95.34

Corn Cob - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	5.0024	3.71	3.04	2960	10.00	14.45
Hg	2425				1660	15.29	31.55
Cd	2244				2172	1.44	3.21
Cr	721				610	2.22	15.40
Multi b							
Pb	1880.0	5.0009	3.93	3.42	1360.0	10.40	27.66
Hg	1153.0				863.0	5.80	25.15
Cd	1230.0				1036.0	3.88	15.77
Cr	360.8				304.8	1.12	15.52
Multi c							
Pb	825.0	5.0073	4.07	3.81	555.0	5.39	32.73
Hg	374.0				352.0	0.44	5.88
Cd	537.0				513.0	0.48	4.47
Cr	124.7				121.3	0.07	2.73
Multi d							
Pb	163.00	5.0041	4.23	4.20	49.00	2.28	69.94
Hg	104.60				30.80	1.47	70.55
Cd	122.60				91.60	0.62	25.29
Cr	31.64				20.96	0.21	33.75
Multi e							
Pb	16.60	5.0024	4.26	4.30	4.30	0.25	74.10
Hg	6.60				0.00	0.13	100.00
Cd	10.74				6.07	0.09	43.48
Cr	3.43				2.00	0.03	41.69

Cellulose Xanthate - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	5.0033	4.56	4.64	1260	43.97	63.58
Hg	2425				135	45.77	94.43
Cd	2244				1954	5.80	12.92
Cr	721				440	5.62	38.97
Multi b							
Pb	1880.0	4.9983	4.62	4.53	480	28.01	74.47
Hg	1153.0				198	19.11	82.83
Cd	1230.0				845	7.70	31.30
Cr	360.8				317	0.88	12.14
Multi c							
Pb	825.0	4.9991	4.51	4.47	130.0	13.90	84.24
Hg	374.0				60.0	6.28	83.96
Cd	537.0				255.0	5.64	52.51
Cr	124.7				86.4	0.77	30.71
Multi d							
Pb	163.00	4.9999	4.60	4.65	0.00	3.26	100.00
Hg	104.60				8.30	1.93	92.07
Cd	122.60				0.90	2.43	99.27
Cr	31.64				25.08	0.13	20.73
Multi e							
Pb	16.60	5.0012	4.60	4.62	0.00	0.33	100.00
Hg	6.60				0.00	0.13	100.00
Cd	10.74				0.02	0.21	99.81
Cr	3.43				2.75	0.01	19.83

Insoluble Starch Xanthate - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	4.9993	4.21	4.19	80	97.69	67.61
Hg	2425				110	95.46	46.31
Cd	2244				1988	11.41	5.12
Cr	721				611	15.26	2.20
Multi b							
Pb	1880.0	5.0005	4.78	5.01	990	47.34	17.80
Hg	1153.0				598	48.14	11.10
Cd	1230.0				1009	17.97	4.42
Cr	360.8				322	10.75	0.78
Multi c							
Pb	825.0	4.9977	4.34	4.33	640	22.42	3.70
Hg	374.0				267	28.61	2.14
Cd	537.0				501	6.70	0.72
Cr	124.7				156	-25.10	-0.63
Multi d							
Pb	163.00	5.0042	4.48	4.55	106.00	34.97	1.14
Hg	104.60				41.70	60.13	1.26
Cd	122.60				95.40	22.19	0.54
Cr	31.64				27.14	14.22	0.09
Multi e							
Pb	16.60	4.9989	4.42	4.38	9.70	41.57	0.14
Hg	6.60				0.00	100.00	0.13
Cd	10.74				5.24	51.21	0.11
Cr	3.43				2.63	23.32	0.02

Kaolinite - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	4.9996	3.67	3.08	3240	4.40	6.36
Hg	2425				1995	8.60	17.73
Cd	2244				2180	1.28	2.85
Cr	721				657	1.28	8.88
Multi b							
Pb	1880.0	5.0013	3.89	3.37	1660.0	4.40	11.70
Hg	1153.0				1175.0	-0.44	-1.91
Cd	1230.0				1075.0	3.10	12.60
Cr	360.8				352.3	0.17	2.36
Multi c							
Pb	825.0	4.9986	4.03	3.82	790.0	0.70	-4.24
Hg	374.0				490.0	-2.32	-31.02
Cd	537.0				530.0	0.14	1.30
Cr	124.7				144.5	-0.40	-15.88
Multi d							
Pb	163.00	5.0012	4.22	4.12	142.00	0.42	12.88
Hg	104.60				97.80	0.14	6.50
Cd	122.60				109.10	0.27	11.01
Cr	31.64				19.76	0.24	37.55
Multi e							
Pb	16.60	5.0009	4.27	4.24	10.60	0.12	36.14
Hg	6.60				3.20	0.07	51.52
Cd	10.74				7.77	0.06	27.65
Cr	3.43				0.74	0.05	78.43



Montmorillonite - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
<b>Multi a</b>							
Pb	3460	5.0006	3.57	2.92	3040	8.40	12.14
Hg	2425				2055	7.40	15.26
Cd	2244				2104	2.80	6.24
Cr	721				468	5.06	35.09
<b>Multi b</b>							
Pb	1880.0	5.0016	3.74	3.15	1430	9.00	23.94
Hg	1153.0				1268	-2.30	-9.97
Cd	1230.0				967	5.26	21.38
Cr	360.8				171	3.79	52.61
<b>Multi c</b>							
Pb	825.0	4.9991	3.91	3.62	575.0	5.00	30.30
Hg	374.0				512.0	-2.76	-36.90
Cd	537.0				398.0	2.78	25.88
Cr	124.7				31.3	1.87	74.90
<b>Multi d</b>							
Pb	163.00	4.9984	4.12	4.00	52.00	2.22	68.10
Hg	104.60				99.10	0.11	5.26
Cd	122.60				40.40	1.64	67.05
Cr	31.64				0.87	0.62	97.25
<b>Multi e</b>							
Pb	16.60	5.0011	4.21	4.12	2.40	0.28	85.54
Hg	6.60				2.90	0.07	56.06
Cd	10.74				2.07	0.17	80.73
Cr	3.43				0.00	0.07	100.00

Peat Moss - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	5.0017	3.62	2.63	1860	31.99	46.24
Hg	2425				1440	19.69	40.62
Cd	2244				2242	0.04	0.09
Cr	721				392	6.58	45.63
Multi b							
Pb	1880.0	5.0016	3.58	2.89	390	29.79	79.26
Hg	1153.0				653	10.00	43.37
Cd	1230.0				834	7.92	32.20
Cr	360.8				87	5.47	75.89
Multi c							
Pb	825.0	5.0007	3.85	2.93	100.0	14.50	87.88
Hg	374.0				196.0	3.56	47.59
Cd	537.0				374.0	3.26	30.35
Cr	124.7				19.3	2.11	84.52
Multi d							
Pb	163.00	4.9994	4.03	3.72	0.00	3.26	100.00
Hg	104.60				0.00	2.09	100.00
Cd	122.60				5.30	2.35	95.68
Cr	31.64				0.17	0.63	99.46
Multi e							
Pb	16.60	4.9998	4.08	3.94	0.00	0.33	100.00
Hg	6.60				0.00	0.13	100.00
Cd	10.74				0.12	0.21	98.88
Cr	3.43				0.00	0.07	100.00

Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
Multi a							
Pb	3460	4.9900	3.97	3.91	200.00	65.33	94.22
Hg	2425				695.00	34.67	71.34
Cd	2244				1462.00	15.67	34.85
Cr	721				270.00	9.04	62.55
Multi b							
Pb	1880	5.0057	4.25	4.13	40.00	36.76	97.87
Hg	1153				358.00	15.88	68.95
Cd	1230				458.00	15.42	62.76
Cr	360.8				231.50	2.58	35.84
Multi c							
Pb	825	4.9994	4.16	4.32	40.00	15.70	95.15
Hg	374				77.00	5.94	79.41
Cd	537				195.00	6.84	63.69
Cr	124.7				124.80	0.00	-0.08
Multi d							
Pb	163	5.0016	4.16	4.50	12.00	3.02	92.64
Hg	104.6				0.40	2.08	99.62
Cd	122.6				53.30	1.39	56.53
Cr	31.64				23.74	0.16	24.97
Multi e							
Pb	16.6	5.000	4.30	4.52	0.50	0.32	96.99
Hg	6.6				0.00	0.13	100.00
Cd	10.74				2.87	0.16	73.28
Cr	3.43				2.31	0.02	32.65

Zeolite - Multi-Metal Batch Testing Data							
Solution	Initial Concentration mg/L	Sorbent Mass g	Original pH	Final pH	Final Concentration mg/L	Sorption mg/g	Percent Sorption %
<b>Multi a</b>							
Pb	3460	4.9961	4.75	5.11	0.00	69.25	100.00
Hg	2425				2075.00	7.01	14.43
Cd	2244				28.00	44.35	98.75
Cr	721				19.00	14.05	97.36
<b>Multi b</b>							
Pb	1880.0	4.9976	4.71	5.14	0.00	37.62	100.00
Hg	1153.0				1053.00	2.00	8.67
Cd	1230.0				16.00	24.29	98.70
Cr	360.8				13.00	6.96	96.40
<b>Multi c</b>							
Pb	825.0	5.0044	4.69	5.12	0.00	16.49	100.00
Hg	374.0				436.00	-1.24	-16.58
Cd	537.0				12.00	10.49	97.77
Cr	124.7				3.60	2.42	97.11
<b>Multi d</b>							
Pb	163.00	4.9984	4.77	5.19	0.00	3.26	100.00
Hg	104.60				61.40	0.86	41.30
Cd	122.60				4.10	2.37	96.66
Cr	31.64				0.57	0.62	98.20
<b>Multi e</b>							
Pb	16.60	4.9983	4.63	5.03	0.20	0.33	98.80
Hg	6.60				0.00	0.13	100.00
Cd	10.74				1.11	0.19	89.66
Cr	3.43				0.26	0.06	92.42

## ZEOLITE STUDIES

Batch Test #1  
UW Zeolite Equilibrium Study  
Synthetic Solution Pb 30K

Sorbent Mass	Initial Concentration Co	Final Concentration Ce	Pb Mass	Capacity	Ce/Co
(g)	(mg/l)	(mg/l)	(mg)	(mg/g)	
Particle size:					
0.5-1.0 mm					
1.0966	33305	28627	467.8	426.59128	0.8595406
5.1259	33305	23107	1019.8	198.95043	0.6937997
7.5064	33305	24013	929.2	123.7877	0.7210029
15.1203	33305	22049	1125.6	74.442967	0.6620327
1.0-4.0 mm					
1.0249	33305	27415	589	574.69021	0.8231497
5.0996	33305	32217	108.8	21.335007	0.9673322
7.4888	33305	23985	932	124.45252	0.7201621
14.9885	33305	1972	3133.3	209.04694	0.0592103
2.0-4.7 mm					
1.0125	33305	29030	427.5	422.22222	0.8716409
5.1575	33305	25233	807.2	156.50994	0.757634
7.5174	33305	5580	2772.5	368.81103	0.1675424
15.0375	33305	2789	3051.6	202.93267	0.0837412

Batch Test #2  
AW & UW Equilibrium Study  
Synthetic Solution Pb 20K

pH

Particle	Sorbent Mass	Acid Washed		Unwashed	
size (mm)	(g)	pH initial	pH final	pH initial	pH final
0.5-1.0	1	4.3	4.46	3.09	4.31
	5	4.21	4.17	3.21	4.45
	7.5	4.25	4.12	3.43	4.58
	15	4.39	4.04	3.65	4.57
1.0-4.0	1	4.4	4.45	3.05	3.74
	5	4.19	4.16	3.18	4.45
	7.5	4.16	4.07	3.32	4.54
	15	4.37	4.00	3.63	4.66
2.0-4.5	1	4.39	4.44	2.99	3.34
	5	4.24	4.21	3.11	4.47
	7.5	4.16	4.09	3.2	4.55
	15	4.45	4.06	3.44	4.66

Batch Test #2  
AW & UW Equilibrium Study  
Synthetic Solution Pb 20K

AW Zeolite

Sorbent Mass	Initial Concentration Co	Final Concentration Ce	Delta C	Pb mass	Capacity
(g)	(mg/l)	(mg/l)	(mg/l)	(mg)	(mg/g)
Particle size:					
0.5-1.0 mm					
1.0742	17738	14181	3557	355.7	331.13014
5.0423	17738	13015	4723	472.3	93.667572
7.5047	17738	10236	7502	750.2	99.964023
15.1368	17738	5522	12216	1221.6	80.70398
1.0-4.0 mm					
1.0588	17738	13861	3877	387.7	366.16925
5.0788	17738	12608	5130	513	101.00811
7.5327	17738	11737	6001	600.1	79.66599
15.1015	17738	7078	10660	1066	70.589014
2.0-4.7 mm					
1.1173	17738	16401	1337	133.7	119.66347
5.1769	17738	13593	4145	414.5	80.067222
7.5389	17738	13213	4525	452.5	60.022019
15.1469	17738	9499	8239	823.9	54.393968



Batch Test #2  
AW & UW Equilibrium Study  
Synthetic Solution Pb 20K

UW Zeolite

Sorbent Mass	Initial Concentration Co	Final Concentration Ce	Delta C	Pb mass	Capacity
(g)	(mg/l)	(mg/l)	(mg/l)	(mg)	(mg/g)
Particle size:					
0.5-1.0 mm					
1.03	14087.00	12546.00	1541.00	154.10	149.61
5.066	14087.00	9327.92	4759.08	475.91	93.94
7.57	14087.00	8608.00	5479.00	547.90	72.38
15.0108	14087.00	5542.00	8545.00	854.50	56.93
1.0-4.0 mm					
1.15	14087.00	13264.00	823.00	82.30	71.57
5.0376	14087.00	9406.75	4680.25	468.02	92.91
7.5186	14087.00	9816.00	4271.00	427.10	56.81
15.0134	14087.00	6748.00	7339.00	733.90	48.88
2.0-4.7 mm					
1.0678	14087.00	13964.00	123.00	12.30	11.52
5.1282	14087.00	10444.38	3642.62	364.26	71.03
7.568	14087.00	11040.00	3047.00	304.70	40.26
15.1168	14087.00	8478.00	5609.00	560.90	37.10

Batch Test #3  
AW Equilibrium Study  
Picatinney Extract

pH

Sample ID	Initial pH	Final pH
1	1.19	1.24
2	1.17	1.2
3	1.13	1.17
4	1.12	1.17

Copper

Sample_ID	Sorbent Mass	Initial Concentration Co	Final Concentration Ce	Capacity
	(g)	(mg/l)	(mg/l)	(mg/g)
1	1	43.53	42.29	0.12
2	5	43.53	38.88	0.09
3	7.5	43.53	41.29	0.03
4	15	43.53	42.49	0.01

Lead

Sample_ID	Sorbent Mass	Initial Concentration Co	Final Concentration Ce	Capacity
	(g)	(mg/l)	(mg/l)	(mg/g)
1	1	12.8	9.59	0.32
2	5	12.8	4.69	0.16
3	7.5	12.8	3.72	0.12
4	15	12.8	2.49	0.07

Batch Test #3  
AW Equilibrium Study  
Picatinney Extract

Zinc

Sample_ID	Sorbent Mass	Initial Concentration Co	Final Concentration Ce	Capacity
	(g)	(mg/l)	(mg/l)	(mg/g)
1	1	45.469	44.74	0.07
2	5	45.469	42.61	0.06
3	7.5	45.469	43.16	0.03
4	15	45.469	43.64	0.01

Batch Test #4  
AW Zeolite Kinetic Study  
Picatinney Extract

Extract Concentrations (Co)

Metal	Concentration
Lead	12.8mg/l
Zinc	45.48mg/l
Copper	40.29mg/l

Lead

Time	Initial pH	Final pH	Final Concentration Ce	Ce/Co	Removal %
(hrs)			(mg/l)		
0.25	1.1	1.03	6.18	0.48	51.72
0.5	1.09	1.09	6.55	0.51	48.83
1	1.16	1.06	6.13	0.48	52.11
2	1.14	1.01	5.66	0.44	55.78
6	1.11	1.09	4.34	0.34	66.09
10	1.11	1.17	3.94	0.31	69.22
15	1.1	1.35	4.44	0.35	65.31
20	1.11	1.06	3.18	0.25	75.16
24	1.11	1.13	3.42	0.27	73.28
30	1.13	1.24	3.22	0.25	74.84

Batch Test #4  
AW Zeolite Kinetic Study  
Picatinney Extract

Copper

Time	Initial pH	Final pH	Final Concentration Ce	Ce/Co	Removal %
(hrs)			(mg/l)		
0.25	1.1	1.03	35.12	0.8716803	12.83
0.5	1.09	1.09	40.896	1.015041	0.00
1	1.16	1.06	39.9	0.9903202	0.97
2	1.14	1.01	39.912	0.990618	0.94
6	1.11	1.09	38.196	0.9480268	5.20
10	1.11	1.17	38.28	0.9501117	4.99
15	1.1	1.35	37.502	0.9308017	6.92
20	1.11	1.06	37.094	0.9206751	7.93
24	1.11	1.13	37.32	0.9262844	7.37
30	1.13	1.24	37.57	0.9324895	6.75

Zinc

Time	Initial pH	Final pH	Final Concentration Ce	Ce/Co	Removal %
(hrs)			(mg/l)		
0.25	1.1	1.03	11.418	0.2510554	74.89
0.5	1.09	1.09	14.5994	0.321007	67.90
1	1.16	1.06	14.9446	0.3285972	67.14
2	1.14	1.01	15.4252	0.3391645	66.08
6	1.11	1.09	15.767	0.3466799	65.33
10	1.11	1.17	16.4102	0.3608223	63.92
15	1.1	1.35	16.8734	0.371007	62.90
20	1.11	1.06	17.287	0.3801011	61.99
24	1.11	1.13	17.7024	0.3892348	61.08
30	1.13	1.24	17.9992	0.3957608	60.42

Batch Test #5  
UW Zeolite Kinetic Study  
Synthetic Solutions

Initial Solution Concentrations (Co)

Metal	Concentration
Lead	856 mg/l
Copper	54 mg/l
Zinc	50.7 mg/l

Lead  
0.5-1.0 mm Zeolite

Time	Final Concentration Ce	Ce/Co	Removal %
(hrs)	(mg/L)		
0.25	0.3	0.000350467	99.964953
0.5	0.2	0.000233645	99.976636
1	0.4	0.00046729	99.953271
2	0.4	0.00046729	99.953271
4	0.6	0.000700935	99.929907
10	1.05	0.001226636	99.877336
15	1.15	0.001343458	99.865654
20	0.9	0.001051402	99.89486
24	0.9	0.001051402	99.89486
30	0	0	100

Batch Test #5  
UW Zeolite Kinetic Study  
Synthetic Solutions

Lead  
1.0-4.0 mm Zeolite

Time	Final Concentration Ce	Ce/Co	Removal %
(hrs)	(mg/L)		
0.25	1.95	0.002278	99.772196
0.5	1.4	0.0016355	99.836449
1	0.9	0.0010514	99.89486
2	2.35	0.0027453	99.725467
4	1.45	0.0016939	99.830607
10	2.15	0.0025117	99.748832
15	0.5	0.0005841	99.941589
20	1.9	0.0022196	99.778037
24	1.3	0.0015187	99.848131
30	1.5	0.0017523	99.824766

Lead  
2.0-4.7 mm Zeolite

Time	Final Concentration Ce	Ce/Co	Removal %
(hrs)	(mg/L)		
0.25	16.55	0.0193341	98.066589
0.5	3.35	0.0039136	99.608645
1	1.5	0.0017523	99.824766
2	0.85	0.000993	99.900701
4	0.4	0.0004673	99.953271
10	0.8	0.0009346	99.906542
15	1.3	0.0015187	99.848131
20	1	0.0011682	99.883178
24	0.8	0.0009346	99.906542
30	0.95	0.0011098	99.889019

Batch Test #5  
UW Zeolite Kinetic Study  
Synthetic Solutions

Zinc  
0.5-1.0 mm Zeolite

Time	Final Concentration Ce	Ce/Co	Removal %
(hrs)	(mg/L)		
0.25	2.4	0.047337278	95.266272
0.5	2.06	0.040631164	95.936884
1	2.16	0.04260355	95.739645
2	3.28	0.06469428	93.530572
4	5.55	0.109467456	89.053254
10	1.29	0.025443787	97.455621
15	1.5	0.029585799	97.04142
20	1.46	0.028796844	97.120316
24	1.98	0.039053254	96.094675
30	2.25	0.044378698	95.56213



Batch Test #5  
UW Zeolite Kinetic Study  
Synthetic Solutions

Zinc  
1.0-4.0 mm Zeolite

Time	Final Concentration Ce	Ce/Co	Removal %
(hrs)	(mg/L)		
0.25	1.38	0.0272189	97.278107
0.5	1.8	0.035503	96.449704
1	1.97	0.038856	96.114398
2	2.79	0.0550296	94.497041
4	5.23	0.1031558	89.684418
10	1.72	0.033925	96.607495
15	2.31	0.0455621	95.443787
20	2.88	0.0568047	94.319527
24	2.33	0.0459566	95.404339
30	4.35	0.0857988	91.420118

Zinc  
2.0-4.7 mm Zeolite

Time	Final Concentration Ce	Ce/Co	Removal %
(hrs)	(mg/L)		
0.25	1.59	0.0313609	96.863905
0.5	1.52	0.0299803	97.001972
1	2	0.0394477	96.055227
2	2.84	0.0560158	94.398422
4	4.46	0.0879684	91.203156
10	3.03	0.0597633	94.023669
15	2.58	0.0508876	94.911243
20	3.7	0.0729783	92.70217
24	3.47	0.0684418	93.155819
30	6.27	0.1236686	87.633136

Batch Test #5  
UW Zeolite Kinetic Study  
Synthetic Solutions

Copper  
2.0-4.7 mm Zeolite

Time	Final Concentration Ce	Ce/Co	Removal %
(hrs)	(mg/L)		
0.25	0.35	0.0064815	99.351852
0.5	0.15	0.0027778	99.722222
1	0.3	0.0055556	99.444444
2	0.4	0.0074074	99.259259
4	1	0.0185185	98.148148
10	2.6	0.0481481	95.185185
15	5.15	0.0953704	90.462963
20	1.25	0.0231481	97.685185
24	4.6	0.0851852	91.481481
30	4.65	0.0861111	91.388889

Batch Test #6  
AW Zeolite  
Selectivity Test

		Pb			Ca		
Sample	Time	Co	Ce	% C Abs.	Co	Ce	% C Abs.
	(hrs)	*(mg/l)	(mg/l)	(mg)	(mg/l)	(mg/l)	(mg)
Solution A:							
1	2	457.6	7.17	98.43	100	22.7	77.30
2	24	457.6	0.395	99.91	100	6.205	93.80
Solution B:							
1	2	38	0.25	99.34	100	0.25	99.75
2	24	38	0.24	99.37	100	0.24	99.76

Batch Test #7  
AW Zeolite Equilibrium Study  
FBH Extract

Sample No.	Sorbent Mass (g)	Lead Concentration, mg/l			Copper Concentration, mg/l			Zinc Concentration, mg/l		
		Co	Ce	Ce/Co	Co	Ce	Ce/Co	Co	Ce	Ce/Co
1	1.24	421	95.92	0.23	6.91	6.40	0.93	2.01	1.70	0.85
2	5.09	421	14.65	0.03	6.91	4.66	0.67	2.01	1.01	0.50
3	7.59	421	9.90	0.02	6.91	3.84	0.56	2.01	0.75	0.37
4	15.05	421	5.26	0.01	6.91	2.32	0.34	2.01	0.41	0.20

Column #1  
Control Column

Time hrs	Influent Concentration mg/L			Effluent Concentration mg/L			Losses Through Column (%)		
	Pb	Cu	Zn	Pb	Cu	Zn	Pb	Cu	Zn
0	466.3	7.12	2.52	422.40	6.43	2.76	9.41	9.62	-9.42
4	464.3	7.11	2.35	460.30	6.98	2.30	0.86	1.74	2.10
8	464.2	7.09	2.33	457.10	6.99	2.29	1.53	1.40	1.77
12	460.8	7.08	2.30	437.90	7.01	2.29	4.97	0.92	0.40

Column #2  
UW Zeolite 3.0 BV/hr

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
376.05	4.45

Effluent					
Sample_ID	pH	Time (hrs)	Volume L	Effluent Pb Conc (Ce) (mg/L)	Ce/Co
UW-2-E0		0.000	0	0	0.000
UW-2-E1	5.04	0.083	0.3	15.41	0.041
UW-2-E2	4.77	0.167	0.6	75.75	0.201
UW-2-E3	4.68	0.250	0.9	113.7	0.302
UW-2-E4	4.65	0.333	1.2	148.55	0.395
UW-2-E5	4.63	0.417	1.5	162.6	0.432
UW-2-E6	4.61	0.500	1.8	165.5	0.440
UW-2-E7	4.6	0.583	2.1	179.55	0.477
UW-2-E8	4.58	0.667	2.4	187.75	0.499
UW-2-E9	4.55	0.750	2.7	199.2	0.530
UW-2-E10	4.56	0.833	3	209.05	0.556
UW-2-E11	4.56	0.917	3.3	232.45	0.618
UW-2-E12	4.55	1.000	3.6	248.5	0.661
UW-2-E15	4.53	1.250	4.5	234	0.622
UW-2-E18	4.52	1.500	5.4	246.7	0.656
UW-2-E21	4.52	1.750	6.3	261.7	0.696
UW-2-E24	4.5	2.000	7.2	305.6	0.813
UW-2-E27	4.47	2.250	8.1	265.2	0.705
UW-2-E30	4.48	2.500	9	282.3	0.751
UW-2-E33	4.48	2.750	9.9	285.9	0.760
UW-2-E36	4.49	3.000	10.8	328.1	0.872
UW-2-E39	4.5	3.250	11.7	298.8	0.795

UW-2-E42	4.48	3.500	12.6	303.7	0.808
UW-2-E45	4.5	3.750	13.5	307.8	0.819
UW-2-E48	4.5	4.000	14.4	354.3	0.942
UW-2-E51	4.5	4.250	15.3	309.6	0.823
UW-2-E54	4.48	4.500	16.2	308.7	0.821
UW-2-E57	4.47	4.750	17.1	313.8	0.834
UW-2-E60	4.46	5.000	18	374.4	0.996
UW-2-E63	4.46	5.250	18.9	317.6	0.845
UW-2-E66	4.46	5.500	19.8	316.4	0.841
UW-2-E72	4.47	6.000	21.6	343.5	0.913
UW-2-E84	4.46	7.000	25.2	369.2	0.982
UW-2-E96	4.45	8.000	28.8	351.2	0.934
UW-2-108	4.46	9.000	32.4	352.9	0.938
UW-2-E120	4.46	10.000	36	357.2	0.950
UW-2-E132	4.47	11.000	39.6	354.9	0.944
UW-2-E144	4.45	12.000	43.2	335.6	0.892

Column #2  
UW Zeolite 3.0 BV/hr

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
6.13	4.45

Effluent					
Sample_ID	pH	Time (Hrs)	Volume L	Effluent Cu Conc (Ce) mg/L	Ce/Co
UW-2-E0		0.000	0	0	0.000
UW-2-E1	5.04	0.083	0.3	1.68	0.274
UW-2-E2	4.77	0.167	0.6	4.668	0.761
UW-2-E3	4.68	0.250	0.9	5.978	0.975
UW-2-E4	4.65	0.333	1.2	5.7675	0.941
UW-2-E5	4.63	0.417	1.5	5.9165	0.965
UW-2-E6	4.61	0.500	1.8	6.3785	1.040
UW-2-E7	4.6	0.583	2.1	6.013	0.981
UW-2-E8	4.58	0.667	2.4	5.9995	0.978
UW-2-E9	4.55	0.750	2.7	6.547	1.068
UW-2-E10	4.56	0.833	3	6.118	0.998
UW-2-E11	4.56	0.917	3.3	6.178	1.008
UW-2-E12	4.55	1.000	3.6	6.65	1.084
UW-2-E15	4.53	1.250	4.5	6.692	1.091
UW-2-E18	4.52	1.500	5.4	6.688	1.091
UW-2-E21	4.52	1.750	6.3	6.7185	1.096
UW-2-E24	4.5	2.000	7.2	6.312	1.029
UW-2-E27	4.47	2.250	8.1	6.6515	1.085
UW-2-E30	4.48	2.500	9	6.8605	1.119
UW-2-E33	4.48	2.750	9.9	6.7355	1.098
UW-2-E36	4.49	3.000	10.8	6.8405	1.116
UW-2-E39	4.5	3.250	11.7	6.8315	1.114
UW-2-E42	4.48	3.500	12.6	6.841	1.116
UW-2-E45	4.5	3.750	13.5	6.859	1.119
UW-2-E48	4.5	4.000	14.4	6.837	1.115

UW-2-E51	4.5	4.250	15.3	6.7695	1.104
UW-2-E54	4.48	4.500	16.2	6.776	1.105
UW-2-E57	4.47	4.750	17.1	6.9425	1.132
UW-2-E60	4.46	5.000	18	6.8805	1.122
UW-2-E63	4.46	5.250	18.9	6.867	1.120
UW-2-E66	4.46	5.500	19.8	6.826	1.113
UW-2-E72	4.47	6.000	21.6	6.8575	1.118
UW-2-E84	4.46	7.000	25.2	6.8995	1.125
UW-2-E96	4.45	8.000	28.8	6.8645	1.119
UW-2-108	4.46	9.000	32.4	6.9505	1.133
UW-2-E120	4.46	10.000	36	6.9615	1.135
UW-2-E132	4.47	11.000	39.6	7.002	1.142
UW-2-E144	4.45	12.000	43.2	6.976	1.138



Column #2  
UW Zeolite 3.0 BV/hr

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.39	4.45

Effluent					
Sample_ID	pH	Time (hrs)	Volume L	Effluent Zn Conc (Ce) (mg/L)	Ce/Co
UW-2-E0		0.000	0	0	0.000
UW-2-E1	5.04	0.083	0.3	0.49315	0.207
UW-2-E2	4.77	0.167	0.6	1.57985	0.662
UW-2-E3	4.68	0.250	0.9	1.83005	0.766
UW-2-E4	4.65	0.333	1.2	1.9172	0.803
UW-2-E5	4.63	0.417	1.5	2.0183	0.845
UW-2-E6	4.61	0.500	1.8	2.19945	0.921
UW-2-E7	4.6	0.583	2.1	2.09555	0.878
UW-2-E8	4.58	0.667	2.4	2.1032	0.881
UW-2-E9	4.55	0.750	2.7	2.18065	0.913
UW-2-E10	4.56	0.833	3	2.17765	0.912
UW-2-E11	4.56	0.917	3.3	2.23355	0.935
UW-2-E12	4.55	1.000	3.6	2.28565	0.957
UW-2-E15	4.53	1.250	4.5	2.25615	0.945
UW-2-E18	4.52	1.500	5.4	2.27415	0.952
UW-2-E21	4.52	1.750	6.3	2.28485	0.957
UW-2-E24	4.5	2.000	7.2	2.14	0.896
UW-2-E27	4.47	2.250	8.1	2.25875	0.946
UW-2-E30	4.48	2.500	9	2.33855	0.979
UW-2-E33	4.48	2.750	9.9	2.28425	0.957
UW-2-E36	4.49	3.000	10.8	2.27	0.951
UW-2-E39	4.5	3.250	11.7	2.3201	0.972
UW-2-E42	4.48	3.500	12.6	2.29115	0.959
UW-2-E45	4.5	3.750	13.5	2.3005	0.963

UW-2-E48	4.5	4.000	14.4	2.31995	0.972
UW-2-E51	4.5	4.250	15.3	2.28435	0.957
UW-2-E54	4.48	4.500	16.2	2.27575	0.953
UW-2-E57	4.47	4.750	17.1	2.31835	0.971
UW-2-E60	4.46	5.000	18	2.28	0.955
UW-2-E63	4.46	5.250	18.9	2.28495	0.957
UW-2-E66	4.46	5.500	19.8	2.29235	0.960
UW-2-E72	4.47	6.000	21.6	2.27	0.951
UW-2-E84	4.46	7.000	25.2	2.28	0.955
UW-2-E96	4.45	8.000	28.8	2.27745	0.954
UW-2-108	4.46	9.000	32.4	2.28	0.955
UW-2-E120	4.46	10.000	36	2.26	0.946
UW-2-E132	4.47	11.000	39.6	2.27	0.951
UW-2-E144	4.45	12.000	43.2	2.26	0.946

Column #3  
AW Zeolite 3.0 BV/hr

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
314.9	4.45

Effluent					
Sample ID	pH	Time (hrs)	Volume L	Effluent Pb Conc (Ce) (mg/l)	Ce/Co
AW-3-E1	4.89	0.08	0	2.7	0.009
AW-3-E2	4.57	0.17	0.3	25.55	0.081
AW-3-E3	4.52	0.25	0.6	53.5	0.170
AW-3-E4	4.49	0.33	0.9	74.9	0.238
AW-3-E5	4.47	0.42	1.2	85.4	0.271
AW-3-E6	4.48	0.50	1.5	100.85	0.320
AW-3-E7	4.45	0.58	1.8	108.4	0.344
AW-3-E8	4.47	0.67	2.1	121.65	0.386
AW-3-E9	4.47	0.75	2.4	126.1	0.400
AW-3-E10	4.45	0.83	2.7	141.95	0.451
AW-3-E11	4.46	0.92	3	143	0.454
AW-3-E12	4.45	1.00	3.3	151.65	0.482
AW-3-E15	4.44	1.25	3.6	164.95	0.524
AW-3-E18	4.45	1.50	4.5	180.9	0.574
AW-3-E21	4.45	1.75	5.4	188.95	0.600
AW-3-E24	4.43	2.00	6.3	191.1	0.607
AW-3-E27	4.45	2.25	7.2	193.3	0.614
AW-3-E30	4.45	2.50	8.1	202.2	0.642
AW-3-E33	4.43	2.75	9	179.25	0.569
AW-3-E36	4.43	3.00	9.9	177.45	0.564
AW-3-E39	4.41	3.25	10.8	211.5	0.672
AW-3-E42	4.42	3.50	11.7	218.1	0.693
AW-3-E45	4.41	3.75	12.6	219.65	0.698
AW-3-E48	4.41	4.00	13.5	210.8	0.669

AW-3-E51	4.41	4.25	14.4	206.9	0.657
AW-3-E54	4.41	4.50	15.3	146.6	0.466
AW-3-E57	4.4	4.75	16.2	180.6	0.574
AW-3-E60	4.4	5.00	17.1	203.45	0.646
AW-3-E63	4.41	5.25	18	211.85	0.673
AW-3-E66	4.41	5.50	18.9	224.7	0.714
AW-3-E72	4.41	5.75	19.8	203.85	0.647
AW-3-E84	4.42	6.00	20.7	191.2	0.607
AW-3-E96	4.41	7.00	21.6	191.8	0.609
AW-3-108	4.41	8.00	25.2	199.4	0.633
AW-3-E120	4.41	9.00	28.8	184.05	0.584
AW-3-E132	4.4	10.00	32.4	204.4	0.649
AW-3-E144	4.4	12.00	36	202.3	0.642

Column #3  
AW Zeolite 3.0 BV/hr

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
5.51	4.45

Effluent					
Sample ID	pH's	Time (Hrs)	Volume L	Effluent Cu Conc (Ce) (mg/l)	Ce/Co
AW-3-E1	4.89	0.08	0.3	0.17	0.03
AW-3-E2	4.57	0.17	0.6	3.63	0.66
AW-3-E5	4.47	0.42	1.5	4.57	0.83
AW-3-E6	4.48	0.50	1.8	4.99	0.91
AW-3-E7	4.45	0.58	2.1	5.04	0.92
AW-3-E8	4.47	0.67	2.4	5.41	0.98
AW-3-E9	4.47	0.75	2.7	5.73	1.04
AW-3-E10	4.45	0.83	3	6.13	1.11
AW-3-E11	4.46	0.92	3.3	5.36	0.97
AW-3-E12	4.45	1.00	3.6	4.71	0.85
AW-3-E15	4.44	1.25	4.5	4.92	0.89
AW-3-E18	4.45	1.50	5.4	5.12	0.93
AW-3-E21	4.45	1.75	6.3	5.34	0.97
AW-3-E24	4.43	2.00	7.2	5.74	1.04
AW-3-E27	4.45	2.25	8.1	5.89	1.07
AW-3-E30	4.45	2.50	9	6.17	1.12
AW-3-E33	4.43	2.75	9.9	4.11	0.75
AW-3-E36	4.43	3.00	10.8	4.58	0.83
AW-3-E39	4.41	3.25	11.7	4.88	0.89
AW-3-E42	4.42	3.50	12.6	5.16	0.94
AW-3-E45	4.41	3.75	13.5	5.37	0.97

AW-3-E48	4.41	4.00	14.4	5.71	1.04
AW-3-E51	4.41	4.25	15.3	5.73	1.04
AW-3-E54	4.41	4.50	16.2	3.17	0.58
AW-3-E57	4.4	4.75	17.1	4.15	0.75
AW-3-E60	4.4	5.00	18	4.32	0.78
AW-3-E63	4.41	5.25	18.9	4.40	0.80
AW-3-E66	4.41	5.50	19.8	4.86	0.88
AW-3-E72	4.41	5.75	20.7	4.88	0.89
AW-3-E84	4.42	6.00	21.6	5.08	0.92
AW-3-E96	4.41	7.00	25.2	4.54	0.82
AW-3-108	4.41	8.00	28.8	4.02	0.73
AW-3-E120	4.41	9.00	32.4	4.85	0.88
AW-3-E132	4.4	10.00	36	4.47	0.81
AW-3-E144	4.4	12.00	43.2	4.51	0.82

Column #3  
AW Zeolite 3.0 BV/hr

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.23	4.45

Effluent					
Sample ID	pH	Time (Hrs)	Volume L	Effluent Zn Conc (Ce) (mg/l)	Ce/Co
AW-3-E1	4.89	0.08	0.3	0.10	0.04
AW-3-E2	4.57	0.17	0.6	1.09	0.49
AW-3-E3	4.52	0.25	0.9	1.18	0.53
AW-3-E4	4.49	0.33	1.2	1.44	0.65
AW-3-E5	4.47	0.42	1.5	1.65	0.74
AW-3-E6	4.48	0.50	1.8	1.97	0.88
AW-3-E7	4.45	0.58	2.1	1.98	0.89
AW-3-E8	4.47	0.67	2.4	2.10	0.94
AW-3-E9	4.47	0.75	2.7	2.03	0.91
AW-3-E10	4.45	0.83	3	2.00	0.89
AW-3-E11	4.46	0.92	3.3	1.56	0.70
AW-3-E12	4.45	1.00	3.6	1.75	0.78
AW-3-E15	4.44	1.25	4.5	1.84	0.82
AW-3-E18	4.45	1.50	5.4	2.04	0.91
AW-3-E21	4.45	1.75	6.3	2.19	0.98
AW-3-E24	4.43	2.00	7.2	2.29	1.02
AW-3-E27	4.45	2.25	8.1	2.24	1.00
AW-3-E30	4.45	2.50	9	2.23	1.00
AW-3-E33	4.43	2.75	9.9	0.83	0.37
AW-3-E36	4.43	3.00	10.8	1.75	0.78
AW-3-E39	4.41	3.25	11.7	1.97	0.88
AW-3-E42	4.42	3.50	12.6	2.08	0.93

AW-3-E45.	4.41	3.75	13.5	2.31	1.03
AW-3-E48	4.41	4.00	14.4	2.33	1.04
AW-3-E51	4.41	4.25	15.3	2.25	1.01
AW-3-E54	4.41	4.50	16.2	1.32	0.59
AW-3-E57	4.4	4.75	17.1	1.68	0.75
AW-3-E60	4.4	5.00	18	1.94	0.87
AW-3-E63	4.41	5.25	18.9	1.04	0.47
AW-3-E66	4.41	5.50	19.8	2.32	1.04
AW-3-E72	4.41	5.75	20.7	2.27	1.01
AW-3-E84	4.42	6.00	21.6	2.36	1.06
AW-3-E96	4.41	7.00	25.2	2.03	0.91
AW-3-108	4.41	8.00	28.8	1.59	0.71
AW-3-E120	4.41	9.00	32.4	1.78	0.80
AW-3-E132	4.4	10.00	36	1.91	0.86
AW-3-E144	4.4	12.00	43.2	2.07	0.93



Column #4  
UW Zeolite 1 BV/hr

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
277.32	4.49

Effluent					
Sample ID	Time (hrs)	pH	Volume L	Effluent Pb Conc (Ce) (mg/l)	Ce/Co
UW-4-E1	0.083	7.18	0.100	3.05	0.01
UW-4-E2	0.167	6.09	0.200	2.85	0.01
UW-4-E3	0.250	5.68	0.300	4.75	0.02
UW-4-E4	0.333	5.43	0.400	4.7	0.02
UW-4-E5	0.417	5.24	0.500	3.95	0.01
UW-4-E6	0.500	5.15	0.600	5	0.02
UW-4-E7	0.583	5.08	0.700	6.7	0.02
UW-4-E8	0.667	5.05	0.800	8.5	0.03
UW-4-E9	0.750	5.01	0.900	9.7	0.03
UW-4-E10	0.833	4.97	1.000	11.85	0.04
UW-4-E11	0.917	4.95	1.100	14.1	0.05
UW-4-E12	1.000	4.9	1.200	15.95	0.06
UW-4-E15	1.250	4.91	1.500	22	0.08
UW-4-E18	1.500	4.84	1.800	19.95	0.07
UW-4-E21	1.750	4.85	2.100	30.7	0.11
UW-4-E24	2.000	4.82	2.400	35.9	0.13
UW-4-E27	2.250		2.700	35.15	0.13
UW-4-E30	2.500		3.000	43.3	0.16
UW-4-E33	2.750		3.300	51.5	0.19
UW-4-E36	3.000	4.77	3.600	57.05	0.21
UW-4-E39	3.250		3.900	63.3	0.23
UW-4-E42	3.500		4.200	69.25	0.25
UW-4-E45	3.750		4.500	76.9	0.28
UW-4-E48	4.000	4.74	4.800	84.9	0.31

UW-4-E51	4.250		5.100	93	0.34
UW-4-E54	4.500		5.400	92.35	0.33
UW-4-E57	4.750		5.700	100.8	0.36
UW-4-E60	5.000	4.71	6.000	102.35	0.37
UW-4-E63	5.250		6.300	107.95	0.39
UW-4-E66	5.500		6.600	115.8	0.42
UW-4-E69	5.750		6.900	116.15	0.42
UW-4-E72	6.000	4.7	7.200	119.7	0.42
UW-4-E84	7.000	4.68	8.400	140.05	0.43
UW-4-E96	8.000	4.67	9.600	156.15	0.51
UW-4-108	9.000	4.66	10.800	171.4	0.56
UW-4-E120	10.000	4.66	12.000	180.05	0.62
UW-4-E132	11.000	4.65	13.200	186.75	0.65
UW-4-E144	12.000	4.65	14.400	198.05	0.67

Column #4  
UW Zeolite 1 BV/hr

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
5.32	4.49

Effluent					
Sample ID	Time (hrs)	pH	Volume (L)	Effluent Cu Conc (Ce) (mg/l)	Ce/Co
UW-4-E1	0.08	7.18	0.1	0.05	0.01
UW-4-E2	0.17	6.09	0.2	0.37	0.07
UW-4-E3	0.25	5.68	0.3	1.84	0.35
UW-4-E4	0.33	5.43	0.4	2.87	0.54
UW-4-E5	0.42	5.24	0.5	3.46	0.65
UW-4-E6	0.50	5.15	0.6	4.06	0.76
UW-4-E7	0.58	5.08	0.7	4.31	0.81
UW-4-E8	0.67	5.05	0.8	4.48	0.84
UW-4-E9	0.75	5.01	0.9	4.46	0.84
UW-4-E10	0.83	4.97	1	4.66	0.88
UW-4-E11	0.92	4.95	1.1	4.85	0.91
UW-4-E12	1.00	4.9	1.2	4.97	0.93
UW-4-E15	1.25	4.91	1.5	5.23	0.98
UW-4-E18	1.50	4.84	1.8	5.19	0.98
UW-4-E21	1.75	4.85	2.1	5.56	1.04
UW-4-E24	2.00	4.82	2.4	5.62	1.06
UW-4-E27	2.25		2.7	5.54	1.04
UW-4-E30	2.50		3	5.66	1.06
UW-4-E33	2.75		3.3	5.94	1.12
UW-4-E36	3.00	4.77	3.6	5.89	1.11
UW-4-E39	3.25		3.9	6.00	1.13
UW-4-E42	3.50		4.2	5.98	1.12
UW-4-E45	3.75		4.5	6.12	1.15

UW-4-E48	4.00	4.74	4.8	6.14	1.15
UW-4-E51	4.25		5.1	6.24	1.17
UW-4-E54	4.50		5.4	5.90	1.11
UW-4-E57	4.75		5.7	6.13	1.15
UW-4-E60	5.00	4.71	6	5.89	1.11
UW-4-E63	5.25		6.3	5.99	1.13
UW-4-E66	5.50		6.6	6.13	1.15
UW-4-E69	5.75		6.9	5.99	1.13
UW-4-E72	6.00	4.7	7.2	6.13	1.13
UW-4-E84	7.00	4.68	8.4	6.17	1.15
UW-4-E96	8.00	4.67	9.6	6.35	1.16
UW-4-108	9.00	4.66	10.8	6.42	1.19
UW-4-E120	10.00	4.66	12	6.35	1.21
UW-4-E132	11.00	4.65	13.2	6.28	1.19
UW-4-E144	12.00	4.65	14.4	6.45	1.18

Column #4  
UW Zeolite 1 BV/hr

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
1.77	4.49

Effluent					
Sample_ID	Time (hrs)	pH	Volume L	Effluent Zn Conc(Ce) (mg/l)	Ce/Co
UW-4-E1	0.08	7.18	0.1	0.03	0.01
UW-4-E2	0.17	6.09	0.2	0.11	0.06
UW-4-E3	0.25	5.68	0.3	0.38	0.22
UW-4-E4	0.33	5.43	0.4	0.60	0.34
UW-4-E5	0.42	5.24	0.5	0.77	0.43
UW-4-E6	0.50	5.15	0.6	0.93	0.52
UW-4-E7	0.58	5.08	0.7	1.06	0.60
UW-4-E8	0.67	5.05	0.8	1.13	0.64
UW-4-E9	0.75	5.01	0.9	1.14	0.64
UW-4-E10	0.83	4.97	1	1.22	0.69
UW-4-E11	0.92	4.95	1.1	1.28	0.72
UW-4-E12	1.00	4.9	1.2	1.33	0.75
UW-4-E15	1.25	4.91	1.5	1.41	0.80
UW-4-E18	1.50	4.84	1.8	1.42	0.80
UW-4-E21	1.75	4.85	2.1	1.54	0.87
UW-4-E24	2.00	4.82	2.4	1.59	0.90
UW-4-E27	2.25		2.7	1.53	0.86
UW-4-E30	2.50		3	1.56	0.88
UW-4-E33	2.75		3.3	1.65	0.93
UW-4-E36	3.00	4.77	3.6	1.73	0.98
UW-4-E39	3.25		3.9	1.74	0.98
UW-4-E42	3.50		4.2	1.74	0.98
UW-4-E45	3.75		4.5	1.80	1.01
UW-4-E48	4.00	4.74	4.8	1.75	0.99

UW-4-E51	4.25		5.1	1.81	1.02
UW-4-E54	4.50		5.4	1.72	0.97
UW-4-E57	4.75		5.7	1.81	1.02
UW-4-E60	5.00	4.71	6	1.74	0.98
UW-4-E63	5.25		6.3	1.78	1.01
UW-4-E66	5.50		6.6	1.82	1.03
UW-4-E69	5.75		6.9	1.76	0.99
UW-4-E72	6.00	4.7	7.2	1.80	0.99
UW-4-E84	7.00	4.68	8.4	1.85	1.02
UW-4-E96	8.00	4.67	9.6	1.96	1.05
UW-4-108	9.00	4.66	10.8	1.98	1.11
UW-4-E120	10.00	4.66	12	1.98	1.11
UW-4-E132	11.00	4.65	13.2	2.13	1.11
UW-4-E144	12.00	4.65	14.4	2.01	1.20

Column #5  
AW Zeolite 1 BV/hr  
Stop Flow Study

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
431	4.56

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Pb Conc (Ce) mg/l	Ce/Co
AW-5-E1A	0.083333	7.69	0.1	1.7	0.004
AW-5-E6A	0.5	4.73	0.6	9.1	0.021
AW-5-E12A	1	4.66	1.2	26.8	0.062
AW-5-15 A	1.25		1.5	35.8	0.083
AW-5-18 A	1.5		1.8	39.5	0.092
AW-5-21 A	1.75		2.1	54	0.125
AW-5-24 A	2	4.62	2.4	65.9	0.153
AW-5-27 A	2.25		2.7	70.5	0.164
AW-5-30 A	2.5		3	81.2	0.188
AW-5-33 A	2.75		3.3	93	0.216
AW-5-36 A	3		3.6	104.5	0.242
AW-5-39 A	3.25		3.9	107.4	0.249
AW-5-42 A	3.5		4.2	132.9	0.308
AW-5-45 A	3.75		4.5	128.7	0.299
AW-5-48 A	4	4.59	4.8	138.3	0.321
AW-5-51 A	6.25		7.5	48.6	0.113
AW-5-54 A	6.5		7.8	71.5	0.166
AW-5-57 A	6.75		8.1	94.6	0.219
AW-5-60A	7		8.4	114.6	0.266
AW-5-63 A	7.25		8.7	133.3	0.309
AW-5-66A	7.5		9	144.9	0.336
AW-5-69 A	7.75		9.3	158.3	0.367
AW-5-72 A	8	4.58	9.6	160.8	0.373
AW-5-75 A	8.25		9.9	156.1	0.362

AW-5-78 A	8.5		10.2	171.4	0.398
AW-5-81 A	8.75		10.5	181.3	0.421
AW-5-84A	9		10.8	194.6	0.452
AW-5-96 A	10		12	217.5	0.505
AW-5-108 A	11	4.58	13.2	231.1	0.536
AW-5-120 A	12		14.4	244	0.566
AW-5-132 A	13		15.6	259.9	0.603



Column #5  
AW Zeolite 1 BV/hr  
Stop Flow Study

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
6.39	4.56

Effluent					
Sample ID	Time hours	pH	Volume L	Effluent Cu Conc (Ce) mg/l	Ce/Co
AW-5-E1A	0.0833	7.69	0.1	0.063	0.01
AW-5-E6A	0.5	4.73	0.6	3.804	0.585
AW-5-E12A	1	4.66	1.2	4.804	0.739
AW-5-15 A	1.25		1.5	5.017	0.772
AW-5-18 A	1.5		1.8	5.324	0.819
AW-5-21 A	1.75		2.1	5.354	0.824
AW-5-24 A	2	4.62	2.4	5.413	0.833
AW-5-27 A	2.25		2.7	5.429	0.835
AW-5-30 A	2.5		3	5.579	0.858
AW-5-33 A	2.75		3.3	5.722	0.88
AW-5-36 A	3		3.6	5.805	0.893
AW-5-39 A	3.25		3.9	5.864	0.902
AW-5-42 A	3.5		4.2	5.929	0.912
AW-5-45 A	3.75		4.5	5.953	0.916
AW-5-48 A	4	4.59	4.8	6.073	0.934
AW-5-51 A	6.25		7.5	5.304	0.816
AW-5-54 A	6.5		7.8	5.845	0.899
AW-5-57 A	6.75		8.1	5.968	0.918
AW-5-60A	7		8.4	6.099	0.938
AW-5-63 A	7.25		8.7	6.101	0.939
AW-5-66A	7.5		9	6.189	0.952
AW-5-69 A	7.75		9.3	6.133	0.944
AW-5-72 A	8	4.58	9.6	6.214	0.956

AW-5-75 A	8.25		9.9	6.204	0.954
AW-5-78 A	8.5		10.2	6.303	0.97
AW-5-81 A	8.75		10.5	6.273	0.965
AW-5-84A	9		10.8	6.305	0.97
AW-5-96 A	10		12	6.451	0.992
AW-5-108 A	11	4.58	13.2	6.432	0.99
AW-5-120 A	12		14.4	6.529	1.004
AW-5-132 A	13		15.6	6.482	0.997

Column #5  
AW Zeolite 1 BV/hr  
Stop Flow Study

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.15	4.56

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Zn Conc (Ce) mg/l	Ce/Co
AW-5-E1A	0.083	7.69	0.1	0.4938	0.229674
AW-5-E6A	0.5	4.73	0.6	0.9327	0.433814
AW-5-E12A	1	4.66	1.2	1.3983	0.650372
AW-5-15 A	1.25		1.5	1.4354	0.667628
AW-5-18 A	1.5		1.8	1.5903	0.739674
AW-5-21 A	1.75		2.1	1.5778	0.73386
AW-5-24 A	2	4.62	2.4	1.6206	0.753767
AW-5-27 A	2.25		2.7	1.6498	0.767349
AW-5-30 A	2.5		3	1.6974	0.789488
AW-5-33 A	2.75		3.3	1.7346	0.806791
AW-5-36 A	3		3.6	1.7785	0.827209
AW-5-39 A	3.25		3.9	1.7983	0.836419
AW-5-42 A	3.5		4.2	1.8222	0.847535
AW-5-45 A	3.75		4.5	1.8409	0.856233
AW-5-48 A	4	4.59	4.8	1.8832	0.875907
AW-5-51 A	6.25		7.5	1.4671	0.682372
AW-5-54 A	6.5		7.8	1.7141	0.797256
AW-5-57 A	6.75		8.1	1.7961	0.835395
AW-5-60A	7		8.4	1.8071	0.840512
AW-5-63 A	7.25		8.7	1.8256	0.849116
AW-5-66A	7.5		9	1.8485	0.859767
AW-5-69 A	7.75		9.3	1.8556	0.86307

AW-5-72 A	8	4.58	9.6	1.866	0.867907
AW-5-75 A	8.25		9.9	1.8862	0.877302
AW-5-78 A	8.5		10.2	1.9043	0.885721
AW-5-81 A	8.75		10.5	1.8943	0.88107
AW-5-84A	9		10.8	1.909	0.887907
AW-5-96 A	10		12	1.9531	0.908419
AW-5-108 A	11	4.58	13.2	1.9451	0.904698
AW-5-120 A	12		14.4	1.9841	0.922837
AW-5-132 A	13		15.6	2.0007	0.930558

Column #6  
UW Zeolite 0.3 BV/hr

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
418.23	4.55

Effluent					
Sample ID	Time	pH	Volume L	Effluent Pb Conc (Ce) mg/l	Ce/Co
AW-6-E1	0.17	7.85	0.06	9.2	0.022
AW-6-E2	0.33		0.12	5.1	0.012
AW-6-E3	0.50		0.18	6	0.014
AW-6-E4	0.67		0.24	7.3	0.017
AW-6-E5	0.83		0.3	5.8	0.014
AW-6-E6	1.00	6.98	0.36	6.1	0.015
AW-6-E7	1.17		0.42	6.9	0.016
AW-6-E8	1.33		0.48	6.6	0.016
AW-6-E9	1.50		0.54	7	0.017
AW-6-E10	1.67		0.6	7.3	0.017
AW-6-E11	1.83		0.66	7.6	0.018
AW-6-E12	2.00	5.34	0.72	7.6	0.018
AW-6-E15	2.50		0.9	8.3	0.020
AW-6-E18	3.00		1.08	9.3	0.022
AW-6-E21	3.50		1.26	10.1	0.024
AW-6-E24	4.00	4.95	1.44	11.2	0.027
AW-6-E27	4.50		1.62	12.5	0.030
AW-6-E30	5.00		1.8	13.5	0.032
AW-6-E33	5.50		1.98	16.1	0.038
AW-6-E36	6.00		2.16	19.5	0.047
AW-6-E39	6.50		2.34	21.6	0.052
AW-6-E42	7.00		2.52	23.4	0.056
AW-6-E45	7.50		2.7	27.6	0.066
AW-6-E48	8.00	4.76	2.88	30.2	0.072

AW-6-E51	8.50		3.06	33.9	0.081
AW-6-E54	9.00		3.24	36.5	0.087
AW-6-E57	9.50		3.42	40.6	0.097
AW-6-E60	10.00	4.71	3.6	45.2	0.108
AW-6-E63	10.50		3.78	48.2	0.115
AW-6-E66	11.00		3.96	53.8	0.129
AW-6-E69	11.50		4.14	57.7	0.138
AW-6-E72	12.00	4.68	4.32	61.5	0.147

Column #6  
UW Zeolite 0.3 BV/hr

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
6.86	4.55

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Cu Conc (Ce) mg/l	Ce/Co
E1	0.17	7.85	0.06	0.048	0.007
E2	0.33		0.12	0.003	0.000
E3	0.50		0.18	0.007	0.001
E4	0.67		0.24	0.204	0.030
E5	0.83		0.3	0.814	0.119
E6	1.00	6.98	0.36	1.511	0.220
E7	1.17		0.42	2.161	0.315
E8	1.33		0.48	2.627	0.383
E9	1.50		0.54	2.913	0.425
E10	1.67		0.6	3.023	0.441
E11	1.83		0.66	3.229	0.471
E12	2.00	5.34	0.72	3.457	0.504
E15	2.50		0.9	3.843	0.560
E18	3.00		1.08	4.144	0.604
E21	3.50		1.26	4.256	0.620
E24	4.00	4.95	1.44	4.437	0.647
E27	4.50		1.62	4.503	0.656
E30	5.00		1.8	4.59	0.669
E33	5.50		1.98	4.771	0.695
E36	6.00		2.16	4.955	0.722
E39	6.50		2.34	5.05	0.736
E42	7.00		2.52	5.037	0.734
E45	7.50		2.7	5.292	0.771
E48	8.00	4.76	2.88	5.262	0.767

E51	8.50		3.06	5.417	0.790
E54	9.00		3.24	5.308	0.774
E57	9.50		3.42	5.483	0.799
E60	10.00	4.71	3.6	5.606	0.817
E63	10.50		3.78	5.643	0.823
E66	11.00		3.96	5.755	0.839
E69	11.50		4.14	5.8	0.845
E72	12.00	4.68	4.32	5.848	0.852



Column #6  
UW Zeolite 0.3 BV/hr

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.14	4.55

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Zn Conc (Ce) mg/l	Ce/Co
E1	0.17	7.85	0.06	0.05	0.024
E2	0.33		0.12	0.05	0.021
E3	0.50		0.18	0.01	0.003
E4	0.67		0.24	0.05	0.024
E5	0.83		0.3	0.16	0.073
E6	1.00	6.98	0.36	0.32	0.150
E7	1.17		0.42	0.44	0.205
E8	1.33		0.48	0.56	0.262
E9	1.50		0.54	0.63	0.294
E10	1.67		0.6	0.68	0.320
E11	1.83		0.66	0.75	0.350
E12	2.00	5.34	0.72	0.79	0.369
E15	2.50		0.9	0.90	0.420
E18	3.00		1.08	1.01	0.473
E21	3.50		1.26	1.07	0.502
E24	4.00	4.95	1.44	1.12	0.522
E27	4.50		1.62	1.19	0.556
E30	5.00		1.8	1.24	0.579
E33	5.50		1.98	1.27	0.595
E36	6.00		2.16	1.33	0.621
E39	6.50		2.34	1.37	0.641
E42	7.00		2.52	1.36	0.634
E45	7.50		2.7	1.45	0.678
E48	8.00	4.76	2.88	1.43	0.666

E51	8.50		3.06	1.49	0.696
E54	9.00		3.24	1.48	0.691
E57	9.50		3.42	1.50	0.700
E60	10.00	4.71	3.6	1.53	0.713
E63	10.50		3.78	1.57	0.731
E66	11.00		3.96	1.59	0.743
E69	11.50		4.14	1.61	0.754
E72	12.00	4.68	4.32	1.64	0.767

Column #7  
AW Zeolite 0.3 BV/hr

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
395.78	4.55

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Pb Conc (Ce) mg/l	Ce/Co
AW-7-E1	0.167	5.78	0.06	5.7	0.014
AW-7-E2	0.333		0.12	2.7	0.007
AW-7-E3	0.500		0.18	1.9	0.005
AW-7-E4	0.667		0.24	1.7	0.004
AW-7-E5	0.833		0.3	1.8	0.005
AW-7-E6	1.000	4.74	0.36	1.6	0.004
AW-7-E7	1.167		0.42	1.6	0.004
AW-7-E8	1.333		0.48	1.6	0.004
AW-7-E9	1.500		0.54	1.7	0.004
AW-7-E10	1.667		0.6	1.8	0.005
AW-7-E11	1.833		0.66	1.7	0.004
AW-7-E12	2.000	4.67	0.72	1.7	0.004
AW-7-E15	2.500		0.9	1.9	0.005
AW-7-E18	3.000		1.08	2.3	0.006
AW-7-E21	3.500		1.26	2.7	0.007
AW-7-E24	4.000	4.65	1.44	3.3	0.008
AW-7-E27	4.500		1.62	4.3	0.011
AW-7-E30	5.000		1.8	5.2	0.013
AW-7-E33	5.500		1.98	6.6	0.017
AW-7-E36	6.000		2.16	7.8	0.020
AW-7-E39	6.500		2.34	10.9	0.028
AW-7-E42	7.000		2.52	13.1	0.033
AW-7-E45	7.500		2.7	15.6	0.039

AW-7-E48	8.000	4.62	2.88	18.3	0.046
AW-7-E51	8.500		3.06	21.2	0.054
AW-7-E54	9.000		3.24	24.1	0.061
AW-7-E57	9.500		3.42	27.3	0.069
AW-7-E60	10.000	4.62	3.6	31.4	0.079
AW-7-E63	10.500		3.78	35.3	0.089
AW-7-E66	11.000		3.96	38.6	0.098
AW-7-E69	11.500		4.14	41.8	0.106
AW-7-E72	12.000	4.62	4.32	47.1	0.119

Column #7  
AW Zeolite 0.3 BV/hr

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
6.87	4.55

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Cu Conc (Ce) mg/l	Ce/Co
AW-7-E0	0		0	0	0
AW-7-E1	0.166667	5.78	0.06	0.07	0.010189
AW-7-E2	0.333333		0.12	0.024	0.003493
AW-7-E3	0.5		0.18	0.03	0.004367
AW-7-E4	0.666667		0.24	0.06	0.008734
AW-7-E5	0.833333		0.3	0.172	0.025036
AW-7-E6	1	4.74	0.36	0.412	0.059971
AW-7-E7	1.166667		0.42	0.763	0.111063
AW-7-E8	1.333333		0.48	1.133	0.16492
AW-7-E9	1.5		0.54	1.517	0.220815
AW-7-E10	1.666667		0.6	1.805	0.262737
AW-7-E11	1.833333		0.66	2.085	0.303493
AW-7-E12	2	4.67	0.72	2.383	0.34687
AW-7-E15	2.5		0.9	2.973	0.432751
AW-7-E18	3		1.08	3.403	0.495342
AW-7-E21	3.5		1.26	3.62	0.526929
AW-7-E24	4	4.65	1.44	3.966	0.577293
AW-7-E27	4.5		1.62	4.157	0.605095
AW-7-E30	5		1.8	4.305	0.626638
AW-7-E33	5.5		1.98	4.536	0.660262
AW-7-E36	6		2.16	4.552	0.662591
AW-7-E39	6.5		2.34	4.783	0.696215
AW-7-E42	7		2.52	4.854	0.70655

AW-7-E45	7.5		2.7	5.003	0.728239
AW-7-E48	8	4.62	2.88	4.998	0.727511
AW-7-E51	8.5		3.06	5.133	0.747162
AW-7-E54	9		3.24	5.156	0.750509
AW-7-E57	9.5		3.42	5.285	0.769287
AW-7-E60	10	4.62	3.6	5.32	0.774381
AW-7-E63	10.5		3.78	5.353	0.779185
AW-7-E66	11		3.96	5.512	0.802329
AW-7-E69	11.5		4.14	5.522	0.803785
AW-7-E72	12	4.62	4.32	5.609	0.816448

Column #7  
AW Zeolite 0.3 BV/hr

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.25	4.55

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Zn Conc (Ce) mg/l	Ce/Co
E1	0.166667	5.78	0.06	0.299	0.132889
E2	0.333333		0.12	0.1016	0.045156
E3	0.5		0.18	0.054	0.024
E4	0.666667		0.24	0.0484	0.021511
E5	0.833333		0.3	0.0477	0.0212
E6	1	4.74	0.36	0.075	0.033333
E7	1.166667		0.42	0.0875	0.038889
E8	1.333333		0.48	0.126	0.056
E9	1.5		0.54	0.1804	0.080178
E10	1.666667		0.6	0.2342	0.104089
E11	1.833333		0.66	0.3017	0.134089
E12	2	4.67	0.72	0.3736	0.166044
E15	2.5		0.9	0.5448	0.242133
E18	3		1.08	0.6844	0.304178
E21	3.5		1.26	0.7952	0.353422
E24	4	4.65	1.44	0.9292	0.412978
E27	4.5		1.62	1.0395	0.462
E30	5		1.8	1.1738	0.521689
E33	5.5		1.98	1.1729	0.521289
E36	6		2.16	1.2689	0.563956
E39	6.5		2.34	1.2746	0.566489
E42	7		2.52	1.3936	0.619378

E45	7.5		2.7	1.3754	0.611289
E48	8	4.62	2.88	1.3947	0.619867
E51	8.5		3.06	1.5074	0.669956
E54	9		3.24	1.5268	0.678578
E57	9.5		3.42	1.502	0.667556
E60	10	4.62	3.6	1.5922	0.707644
E63	10.5		3.78	1.5571	0.692044
E66	11		3.96	1.633	0.725778
E69	11.5		4.14	1.6421	0.729822
E72	12	4.62	4.32	1.6174	0.718844



Column #8  
AW Zeolite 1 BV/hr

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
441.1	4.53

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Pb Conc (Ce) mg/l	Ce/Co
AW-8-E1	0.083333	5.4	0.1	4.4	0.009975
AW-8-E2	0.166667		0.2	4.3	0.009748
AW-8-E3	0.25		0.3	4.6	0.010428
AW-8-E4	0.333333		0.4	6.2	0.014056
AW-8-E5	0.416667		0.5	8.3	0.018817
AW-8-E6	0.5	4.51	0.6	11.2	0.025391
AW-8-E7	0.583333		0.7	14.5	0.032872
AW-8-E8	0.666667		0.8	17.7	0.040127
AW-8-E9	0.75		0.9	21.6	0.048968
AW-8-E10	0.833333		1	25.7	0.058263
AW-8-E11	0.916667		1.1	30.1	0.068238
AW-8-E12	1	4.43	1.2	33	0.074813
AW-8-E15	1.25		1.5	46.9	0.106325
AW-8-E18	1.5		1.8	59	0.133757
AW-8-E21	1.75		2.1	70.7	0.160281
AW-8-E24	2	4.4	2.4	84.4	0.19134
AW-8-E30	2.5		3	104.4	0.236681
AW-8-E36	3		3.6	121.9	0.276355
AW-8-E42	3.5		4.2	140	0.317388
AW-8-E48	4	4.39	4.8	155.5	0.352528
AW-8-E54	4.5		5.4	171	0.387667
AW-8-E60	5		6	179.2	0.406257
AW-8-E66	5.5		6.6	195.6	0.443437

AW-8-E72	6		7.2	206.6	0.468375
AW-8-E84	7		8.4	218.3	0.494899
AW-8-E96	8	4.38	9.6	240.8	0.545908
AW-8-E108	9		10.8	251.5	0.570165
AW-8-E120	10		12	264.6	0.599864
AW-8-E132	11	4.38	13.2	275.1	0.623668
AW-8-E144	12	4.37	14.4	284.1	0.644072

Column #8  
AW Zeolite 1 BV/hr

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
6.75	4.53

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Cu Conc (Ce) mg/l	Ce/Co
AW-8-E1	0.083333	5.4	0.1	0.035	0.005185
AW-8-E2	0.166667		0.2	0.781	0.115704
AW-8-E3	0.25		0.3	2.278	0.337481
AW-8-E4	0.333333		0.4	3.01	0.445926
AW-8-E5	0.416667		0.5	3.417	0.506222
AW-8-E6	0.5	4.51	0.6	3.98	0.58963
AW-8-E7	0.583333		0.7	4.238	0.627852
AW-8-E8	0.666667		0.8	4.409	0.653185
AW-8-E9	0.75		0.9	4.58	0.678519
AW-8-E10	0.833333		1	4.728	0.700444
AW-8-E11	0.916667		1.1	4.841	0.717185
AW-8-E12	1	4.43	1.2	4.912	0.727704
AW-8-E15	1.25		1.5	5.19	0.768889
AW-8-E18	1.5		1.8	5.383	0.797481
AW-8-E21	1.75		2.1	5.394	0.799111
AW-8-E24	2	4.4	2.4	5.64	0.835556
AW-8-E30	2.5		3	5.823	0.862667
AW-8-E36	3		3.6	5.943	0.880444
AW-8-E42	3.5		4.2	6.014	0.890963
AW-8-E48	4	4.39	4.8	5.992	0.887704
AW-8-E54	4.5		5.4	6.088	0.901926
AW-8-E60	5		6	6.129	0.908

AW-8-E66	5.5		6.6	6.218	0.921185
AW-8-E72	6		7.2	6.3	0.933333
AW-8-E84	7		8.4	6.289	0.931704
AW-8-E96	8	4.38	9.6	6.406	0.949037
AW-8-E108	9		10.8	6.443	0.954519
AW-8-E120	10		12	6.469	0.95837
AW-8-E132	11	4.38	13.2	6.496	0.96237
AW-8-E144	12	4.37	14.4	6.598	0.977481

Column #8  
AW Zeolite 1 BV/hr

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.12	4.53

Effluent					
Sample ID	Time (Hrs)	pH	Volume L	Effluent Zn Conc (Ce) mg/l	Ce/Co
AW-8-E0	0		0	0	0
AW-8-E1	0.083333	5.4	0.1	0.3228	0.152264
AW-8-E2	0.166667		0.2	0.1969	0.092877
AW-8-E3	0.25		0.3	0.3845	0.181368
AW-8-E4	0.333333		0.4	0.5888	0.277736
AW-8-E5	0.416667		0.5	0.7151	0.337311
AW-8-E6	0.5	4.51	0.6	0.8922	0.420849
AW-8-E7	0.583333		0.7	0.9922	0.468019
AW-8-E8	0.666667		0.8	1.0754	0.507264
AW-8-E9	0.75		0.9	1.1456	0.540377
AW-8-E10	0.833333		1	1.2016	0.566792
AW-8-E11	0.916667		1.1	1.2524	0.590755
AW-8-E12	1	4.43	1.2	1.2839	0.605613
AW-8-E15	1.25		1.5	1.4258	0.672547
AW-8-E18	1.5		1.8	1.4873	0.701557
AW-8-E21	1.75		2.1	1.5211	0.7175
AW-8-E24	2	4.4	2.4	1.6107	0.759764
AW-8-E30	2.5		3	1.6988	0.801321
AW-8-E36	3		3.6	1.7978	0.848019
AW-8-E42	3.5		4.2	1.8232	0.86
AW-8-E48	4	4.39	4.8	1.8352	0.86566
AW-8-E54	4.5		5.4	1.8925	0.892689

AW-8-E60	5		6	1.9071	0.899575
AW-8-E66	5.5		6.6	1.9074	0.899717
AW-8-E72	6		7.2	1.9605	0.924764
AW-8-E84	7		8.4	1.9583	0.923726
AW-8-E96	8	4.38	9.6	2.0197	0.952689
AW-8-E108	9		10.8	2.0361	0.960425
AW-8-E120	10		12	2.0118	0.948962
AW-8-E132	11	4.38	13.2	2.0394	0.961981
AW-8-E144	12	4.37	14.4	2.0487	0.966368

Column #9  
UW Zeolite 0.3 BV/hr  
7 day Study

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
465.55	

Effluent				
Sample ID	Time (Hrs)	Volume L	Effluent Pb Conc (Ce) mg/l	Ce/Co mg/l
UW-9-E1	24	8.64	8.3	0.02
UW-9-E2	48	17.28	157.9	0.34
UW-9-E3	72	25.92	303.7	0.66
UW-9-E4	96	34.56	330.1	0.72
UW-9-E5	120	43.2	349.7	0.76
UW-9-E6	144	51.84	380.3	0.83
UW-9-E7	166	59.76	428.6	0.93

Column #9  
UW Zeolite 0.3 BV/hr  
7 day Study

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
6.92	

Effluent				
Sample ID	Time (Hrs)	Volume L	Effluent Cu Conc (Ce) mg/l	Ce/Co
UW-9-E0	0	0	0	0.00
UW-9-E1	24	8.64	0.142	0.02
UW-9-E2	48	17.28	6.295	0.91
UW-9-E3	72	25.92	6.657	0.96
UW-9-E4	96	34.56	7.058	1.02
UW-9-E5	120	43.2	7.023	1.01
UW-9-E6	144	51.84	7.044	1.02



Column #9  
UW Zeolite 0.3 BV/hr  
7 day Study

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.38	

Effluent				
Sample ID	Time (Hrs)	Volume L	Effluent Zn Conc (Ce) mg/l	Ce/Co
UW-9-E1	24	8.64	0.07	0.03
UW-9-E2	48	17.28	2.08	0.88
UW-9-E3	72	25.92	2.25	0.95
UW-9-E4	96	34.56	2.34	0.99
UW-9-E5	120	43.2	2.31	0.98
UW-9-E6	144	51.84	2.30	0.97

Column #10  
UW Zeolite 0.3 BV/hr: 0.2-1.0 mm Material

Lead

Influent	
Average Pb Concentration (Co) mg/l	pH
424.25	

Effluent				
Sample ID	Time (Hrs)	Volume L	Effluent Pb Conc (Ce) mg/l	Ce/Co
UW-10-E1	0.167	0.06	0.03	7.080e-05
UW-10-E3	0.500	0.18	0.2	4.720e-04
UW-10-E6	1.000	0.36	0.26	6.130e-04
UW-10-E9	1.500	0.54	0.2	4.720e-04
UW-10-E12	2.000	0.72	0.16	3.770e-04
UW-10-E15	2.500	0.9	0.11	2.590e-04
UW-10-E18	3.000	1.08	0.11	2.590e-04
UW-10-E21	3.500	1.26	0.1	2.360e-04
UW-10-E24	4.000	1.44	0.11	2.590e-04
UW-10-E27	4.500	1.62	0.12	2.830e-04
UW-10-E30	5.000	1.8	0.1	2.360e-04
UW-10-E33	5.500	1.98	0.11	2.590e-04
UW-10-E36	6.000	2.16	0.1	2.360e-04
UW-10-E39	6.500	2.34	0.11	2.590e-04
UW-10-E42	7.000	2.52	0.1	2.360e-04
UW-10-E45	7.500	2.7	0.1	2.360e-04
UW-10-E48	8.000	2.88	0.09	2.120e-04
UW-10-E51	8.500	3.06	0.1	2.360e-04
UW-10-E54	9.000	3.24	0.1	2.360e-04
UW-10-E57	9.500	3.42	0.09	2.120e-04
UW-10-E60	10.000	3.6	0.07	1.650e-04
UW-10-E63	10.500	3.78	0.09	2.120e-04
UW-10-E66	11.000	3.96	0.06	1.420e-04

UW-10-E69	11.500	4.14	0.05	1.180e-04
UW-10-E72	12.000	4.32	0.08	1.890e-04

Column #10  
UW Zeolite 0.3 BV/hr: 0.2-1.0 mm Material

Copper

Influent	
Average Cu Concentration (Co) mg/l	pH
6.90	

Effluent				
Sample ID	Time (Hrs)	Volume L	Effluent Cu Conc (Ce) mg/l	Ce/Co
UW-10-E1	0.17	0.06	0.088	1.275e-02
UW-10-E3	0.5	0.18	0.076	1.101e-02
UW-10-E6	1	0.36	0.08	1.159e-02
UW-10-E9	1.5	0.54	0.157	2.275e-02
UW-10-E12	2	0.72	0.906	1.313e-01
UW-10-E15	2.5	0.9	1.892	2.742e-01
UW-10-E18	3	1.08	2.531	3.668e-01
UW-10-E21	3.5	1.26	3.044	4.412e-01
UW-10-E24	4	1.44	3.263	4.729e-01
UW-10-E27	4.5	1.62	3.469	5.028e-01
UW-10-E30	5	1.8	3.822	5.539e-01
UW-10-E33	5.5	1.98	3.931	5.697e-01
UW-10-E36	6	2.16	4.156	6.023e-01
UW-10-E39	6.5	2.34	4.388	6.359e-01
UW-10-E42	7	2.52	4.511	6.538e-01
UW-10-E45	7.5	2.7	4.712	6.829e-01
UW-10-E48	8	2.88	4.786	6.936e-01
UW-10-E51	8.5	3.06	4.847	7.025e-01
UW-10-E54	9	3.24	5.056	7.328e-01
UW-10-E57	9.5	3.42	5.16	7.478e-01
UW-10-E60	10	3.6	5.197	7.532e-01
UW-10-E63	10.5	3.78	5.351	7.755e-01
UW-10-E66	11	3.96	5.41	7.841e-01

UW-10-E69	11.5	4.14	5.547	8.039e-01
UW-10-E72	12	4.32	5.601	8.117e-01

Column #10  
UW Zeolite 0.3 BV/hr: 0.2-1.0 mm Material

Zinc

Influent	
Average Zn Concentration (Co) mg/l	pH
2.01	

Effluent				
Sample ID	Time (Hrs)	Volume L	Effluent Zn Conc (Ce) mg/l	Ce/Co
UW-10-E1	0.166667	0.06	0.0333	0.01665
UW-10-E3	0.5	0.18	0.0282	0.0141
UW-10-E6	1	0.36	0.0852	0.0426
UW-10-E9	1.5	0.54	0.0937	0.04685
UW-10-E12	2	0.72	0.2296	0.1148
UW-10-E15	2.5	0.9	0.4242	0.2121
UW-10-E18	3	1.08	0.5515	0.27575
UW-10-E21	3.5	1.26	0.6425	0.32125
UW-10-E24	4	1.44	0.6853	0.34265
UW-10-E27	4.5	1.62	0.7947	0.39735
UW-10-E30	5	1.8	0.9114	0.4557
UW-10-E33	5.5	1.98	0.9667	0.48335
UW-10-E36	6	2.16	1.0557	0.52785
UW-10-E39	6.5	2.34	1.1295	0.56475
UW-10-E42	7	2.52	1.1615	0.58075
UW-10-E45	7.5	2.7	1.2672	0.6336
UW-10-E48	8	2.88	1.2593	0.62965
UW-10-E51	8.5	3.06	1.287	0.6435
UW-10-E54	9	3.24	1.3631	0.68155
UW-10-E57	9.5	3.42	1.3972	0.6986
UW-10-E60	10	3.6	1.4169	0.70845
UW-10-E63	10.5	3.78	1.4726	0.7363
UW-10-E66	11	3.96	1.4987	0.74935

UW-10-E69	11.5	4.14	1.5631	0.78155
UW-10-E72	12	4.32	1.5571	0.77855